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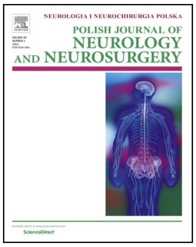

Original research article

Software-assisted morphometry and volumetry of the lumbar spine

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ABSTRACT

The aim of the study was to measure volumes of the lumbar vertebral bodies with use dedicated Computed Tomography (CT) workstation software to predict expected volume of PMMA for vertebroplasty and supplement calculations using computed tomography scanogram. Quantitative CT scans of 87 women's (mean age 69.4 years; SD 10.9) and 15 men's (mean age 64.3 years; SD 11.8) lumbar spines were analyzed; this made a total of 379 vertebrae. The population of patients was divided into three groups depending on measured BMD value, in accordance with American College of Radiology Practice Parameter for the Performance of Quantitative Computed Tomography (QCT) Bone Densitometry. With the use of the general linear model and least squares means groups were compared regarding vertebral volume, anterior, middle, and posterior vertebral heights.

Morphometric parameters tended to be greater in males than in females, in a population of diversified bone mineral density. BMD result should be considered as the modifying factor for preoperative planning of the bone cement volume to be deposited inside the vertebra. Vertebral body volumetry might prove to be a useful tool in pre-operative planning as well as an alternative for treatment monitoring after minimally invasive spinal procedures.

1. Introduction

During percutaneous cement augmentation procedures, the volume of the vertebral body may play a role in preoperative planning of cement volume required for the adequate intervention [1–6]. A few authors mentioned that the tiny volume of cement might be needed to achieve satisfactory clinical pain relief [1,7]. However, other authors strongly suggest that the aim of the vertebral body augmentation is to restore its shape and biomechanics [8–14]. Restored biomechanics of the vertebra was pointed as a crucial factor preventing following vertebral fractures in the osteoporotic spine [15–17]. Another aspect of vertebral

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body volume calculation refers to prevent cement leaks [18,19].

In recent years, a significant trend toward the development of quantitative tools has been seen applied in medical imaging [20]. These tools are increasingly utilized in research, but most importantly in a clinical setting, where they prove their usefulness. Since time management becomes an important issue in everyday surgical practice, surgeons strive to enhance their pre-operative planning with emerging technology [21,22].

Growing number of imaging modalities and a variety of images they produce prompt a need for a quantitative tool to be versatile. Nowadays, with the accumulation of images, one must take patient's safety into consideration, and since radiation exposure remains a serious concern [23].

Despite numerous and recent studies regarding lumbar morphometry among different populations, many volumetric issues remain unanswered [24–31]. Usually, vertebral body volume is calculated from volumetric reformations from computed tomography (CT). Rarely authors utilize computed tomography scanograms as an additional source of measurements [32,33].

The aim of the study was to measure volumes of the lumbar vertebral bodies with use dedicated Computed Tomography (CT) workstation software to predict expected volume of PMMA for vertebroplasty and supplement calculations using computed tomography scanogram.

2. Materials and methods

This study was performed by the ethical standards of the Helsinki Declaration. The Institutional Review Board approved the study (No. KB 22/2012, issued January 17, 2012). Computed tomography (CT) scans of 87 women (mean age 69.4 years; SD 10.9) and 15 men (mean age 64.3 years; SD 11.8) diagnosed and treated in our Department were obtained.

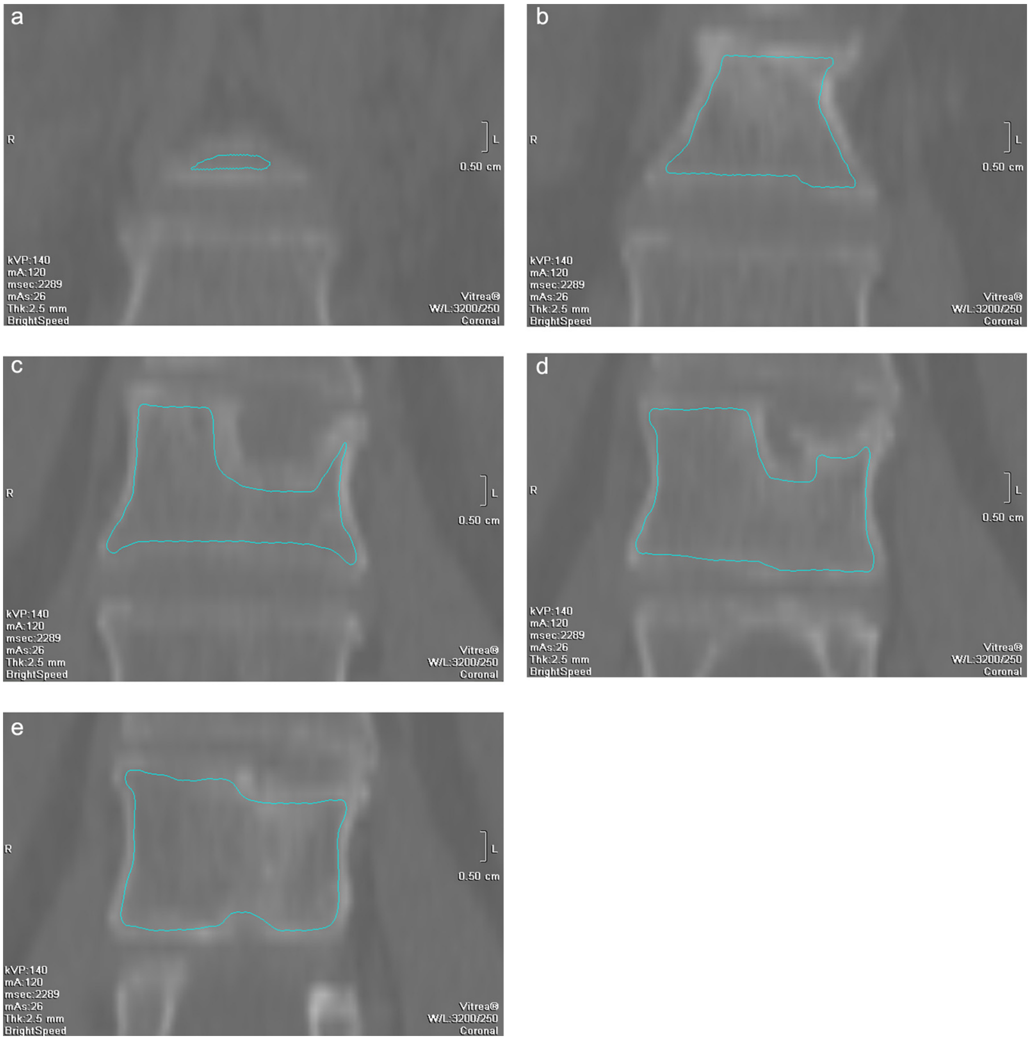


Fig. 1 – (a) The first slice outline in coronal view of the vertebral body at the point of first cancellous bone appearance. (b) The slice outline in coronal view of the vertebral body at the point of visibility of both (superior and inferior) endplates. (c) The slice outline in coronal view of the vertebral body in the middle of the vertebral body. (d) The slice outline in coronal view of the vertebral body at the point of the almost last cancellous bone appearance. (e) The slice outline in coronal view of the vertebral body at the point of the last cancellous bone appearance.

102 quantitative CT scans of lumbar spines were analyzed; this made a total of 379 vertebrae, due to a variable number of vertebra scanned per patient.

2.1. *Measuring procedure*

The vertebral body volumes were measured from the predefined bone window CT IAC 3200/250 using Vitrea 2 Workstation Software (Vitrea 2 Workstation, Vital Images Inc., Minnetonka, MN, USA). The patients were scanned in a 16 row CT scanner (GE Healthcare BrightSpeed, Waukesha, WI, USA) using a reference phantom for Quantitative Computed Tomography (QCT) to evaluate BMD values.

The analysis of the obtained vertebral body scans consisted of following stages:

- the proper bone window selection;
- the crosshairs placement centrally in the vertebral body in every plane (sagittal, coronal, axial);
- the visual components set; and
- the zoom to adjust the image for the researcher's convenience.

A manual subcortical outline of five slices of each vertebral body was made. The first outline beginning from the front of the vertebral body was the one where there appeared first cancellous bone (Fig. 1a). Then was the one where there were both (superior and inferior) endplates seen (Fig. 1b). The third slice was outlined in the middle of the vertebral body (Fig. 1c).

Fourth between third and fifth slice and finally fifth was made on the last slice containing cancellous bone (Fig. 1d and e). Subsequently the volume of the vertebral body was calculated. All slices were outlined in coronal view. The adequacy of the described technique was proven by sculpting the form that had been outlined. Prior attempts with the use of sagittal and axial view failed to encompass the adequate volume of the vertebral body, given the scanning protocol.

The novel approach was to use additionally computed tomography scanogram to analyze vertebral bodies with dedicated software. To the best of our knowledge, this is the first study to measure vertebral body volume with this approach.

The scout views used in this study consisted of lateral low energy 2D scanograms extending from the thoracolumbar (Th12–L1) to the lumbosacral junction (L5–S1). Semi-automated quantitative vertebral morphometry was performed using a model-based shape recognition technology. Morphometry provides standard six-point analysis, accompanied by detailed annotation to define the shape of each vertebra between T4 and L5 (SpineAnalyzer, Optasia Medical, Cheadle, UK) (Fig. 2). The software was validated in previous studies [21,22].

Lossless TIFF images were loaded and displayed. After manual labeling of vertebrae of interest (points in the approximate center of each vertebra) the algorithm automatically identified vertebral body margins, drew contours, and placed points for standard six-point morphometry. All points were reviewed by the operator and manually adjusted if necessary according to Hurxthal criteria [34]. In cases with the marked osteophyte formation, the best representation of corner landmarks was achieved following Goh et al. [26]. The program computed vertebral heights, height ratios, and deformities indicative of vertebral fracture, in accordance with Genant's semiquantitative scale: grade 0 (<20% deformity), grade 1 (≥20% deformity), grade 2 (≥25% deformity), and grade 3 (≥40% deformity) [35].

Statistical analysis was performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

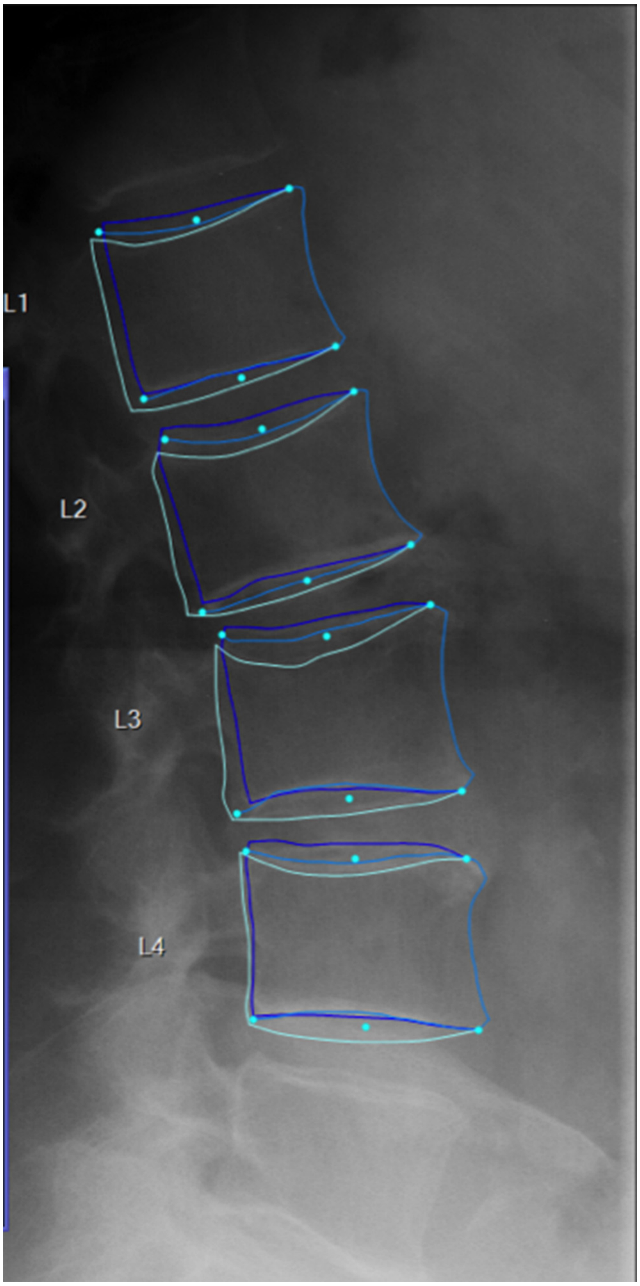


Fig. 2 – The result of semi-automated quantitative vertebral morphometry of L1 to L5 vertebra (SpineAnalyzer, Optasia Medical, Cheadle, UK).

3. Results

The data represent vertebrae classified as non-deformed according to Genant's semiquantitative scale [35]. Student *t*-test for paired observations was calculated for vertebral volume. There was no significant difference between compared groups in respect of variance measured by standard deviations ($p = 0.559$). Mean vertebral volume was significantly greater in men than in women (27.79 vs. 20.33 [cm^3], $p < 0.0001$). Similarly, mean anterior vertebral height was greater in men than in women (49.55 vs. 47.02, $p = 0.0005$). The middle height diameter and posterior height were also significantly higher (47.05 vs. 43.95, $p < 0.0001$ and 51.56 vs. 47.60, $p < 0.0001$), respectively. Mean BMD differences between male and female patients were not significant in our group (58.45 vs. 66.89 [mg/cm^3], $p = 0.201$).

Pearson correlation coefficients were calculated for all variables. The volume showed positive correlation with weight and height of the patient ($r = 0.33$, $r = 0.49$, respectively), both statistically significant ($p < 0.0001$). Measured vertebral heights also correlated positively with volume, presenting a stronger, significant relationship, especially for anterior and middle height ($r = 0.60$ and $r = 0.61$, respectively, $p < 0.0001$). Posterior height correlation coefficient was $r = 0.50$ ($p < 0.0001$). A negative correlation was observed for age and bone mineral density, although both weak ($r = -0.13$ and $r = -0.11$, respectively), only first proved to be significant ($p = 0.012$ and $p = 0.059$). Among ratios calculated from vertebral heights only, biconcave ratio showed statistical significance ($r = 0.31$, $p < 0.0001$). As for the relationship between age and morphological parameters of vertebrae, the only significant correlation was found between anterior heights ($r = -0.13$, $p = 0.023$). Pearson coefficient for age and BMD was $r = -0.31$, $p < 0.0001$.

Bone mineral density revealed a characteristic pattern, i.e. among three vertebral heights only middle correlated positively and significantly, $r = 0.13$ compared to $r = -0.04$ and $r = -0.08$ for anterior and posterior, respectively (both $p > 0.05$). Similarly, calculated biconcave ratio showed a positive relationship ($r = 0.16$, $p = 0.01$), when the remaining ratios coefficients were negative and insignificant. Additionally, the prevalence of biconcave deformity yielded a result of $r = -0.21$, $p = 0.0008$ while the presence of the other deformities was insignificant. The remaining relationships between morphological parameters were collected in Table 1.

The population of patients was divided into three groups depending on measured BMD value. Patients with values of 120 mg/cm^3 and more were considered as normal (GROUP 0); 80–120 mg/cm^3 were annotated as moderate (GROUP 1) and finally below 80 mg/cm^3 were poor (GROUP 2) – in accordance with American College of Radiology Practice Parameter for the Performance of Quantitative Computed Tomography (QCT) Bone Densitometry. With the use of the general linear model and least squares means groups were compared regarding vertebral volume, anterior, middle, and posterior vertebral heights. Results are summarized in Tables 1–4 and Graphs 1 and 2.

Table 1 – Significance of differences (*p* values) between BMD groups regarding vertebral volume. Group 0 – 110–145 and more mg/cm^3, Group 1 – 80–110 mg/cm^3, Group 2 – <80 mg/cm^3. Significance level $p < 0.05$.

Vertebral volume	Group 0	Group 1	Group 2
Group 0		0.6754	0.3818
Group 1	0.6754		0.6804
Group 2	0.3818	0.6804	

Table 2 – Significance of differences (*p* values) between BMD groups regarding anterior vertebral height. Group 0 – 110–145 and more mg/cm^3, Group 1 – 80–110 mg/cm^3, Group 2 – <80 mg/cm^3. Significance level $p < 0.05$.

Anterior height	Group 0	Group 1	Group 2
Group 0		0.5124	0.7976
Group 1	0.5124		0.5073
Group 2	0.7976	0.5073	

Table 3 – Significance of differences (*p* values) between BMD groups regarding middle vertebral height. Group 0 – 110–145 and more mg/cm^3, Group 1 – 80–110 mg/cm^3, Group 2 – <80 mg/cm^3. Significance level $p < 0.05$.

Middle height	Group 0	Group 1	Group 2
Group 0		0.5677	0.1870
Group 1	0.5677		0.0136
Group 2	0.1870	0.0136	

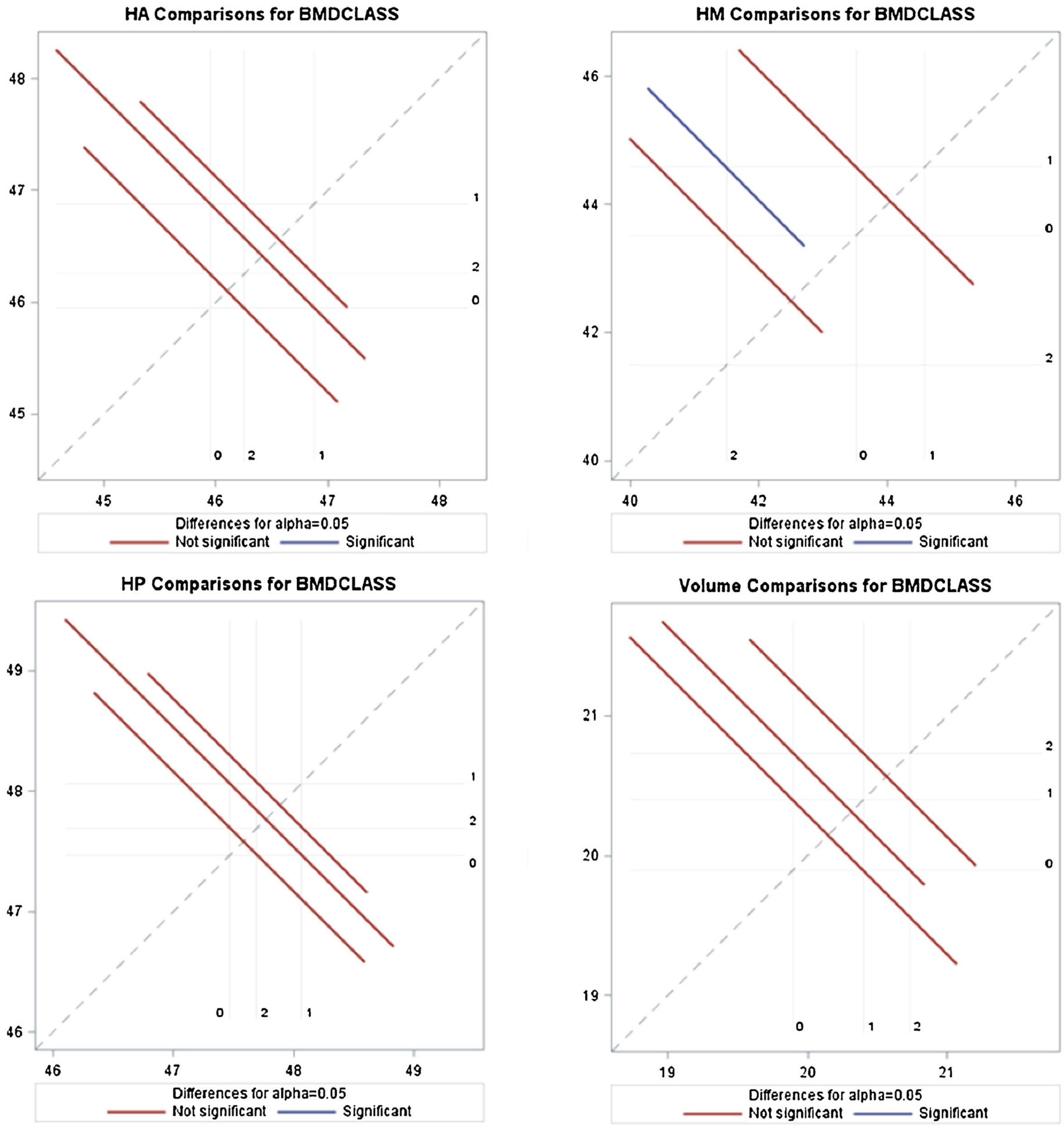
Table 4 – Significance of differences (*p* values) between BMD groups regarding posterior vertebral height. Group 0 – 110–145 and more mg/cm^3, Group 1 – 80–110 mg/cm^3, Group 2 – <80 mg/cm^3. Significance level $p < 0.05$.

Posterior height	Group 0	Group 1	Group 2
Group 0		0.6643	0.8375
Group 1	0.6643		0.6921
Group 2	0.8375	0.6921	

4. Discussion

Many authors have described the morphometric parameters of the spinal vertebrae measured based on several different imaging modalities (magnetic resonance imaging, computed tomography, plain image, direct specimen measurement and quantitative 3D anatomic technique) [24,25,27,29,36]. It is crucial not to multiply unnecessary examination since radiation exposure remains a serious safety concern [23].

The retrospective analysis of CT scans being made to provide QCT protocol (Quantitative Computed Tomography) was performed in this study. Initial scanogram (scout) was used for morphometry, since some patients suffered from axial misalignment of the spine in the coronal plane, for example, scoliosis or fracture encompassing a lateral portion of the vertebral body. Thus, it was impossible to achieve mid-sagittal plane for all vertebrae at the same time on a CT scan, which is necessary for automated morphometry. A scout view, though inferior to conventional radiograph regarding resolution, is utilized with growing interest in assessing vertebral fracture. Scouts were used in prior studies involving semi-quantitative, automated morphometric analysis and proved to be clinically reliable [21,22]. Radiographs' main disadvantage is a parallax distortion present in cone-beam imaging geometry,



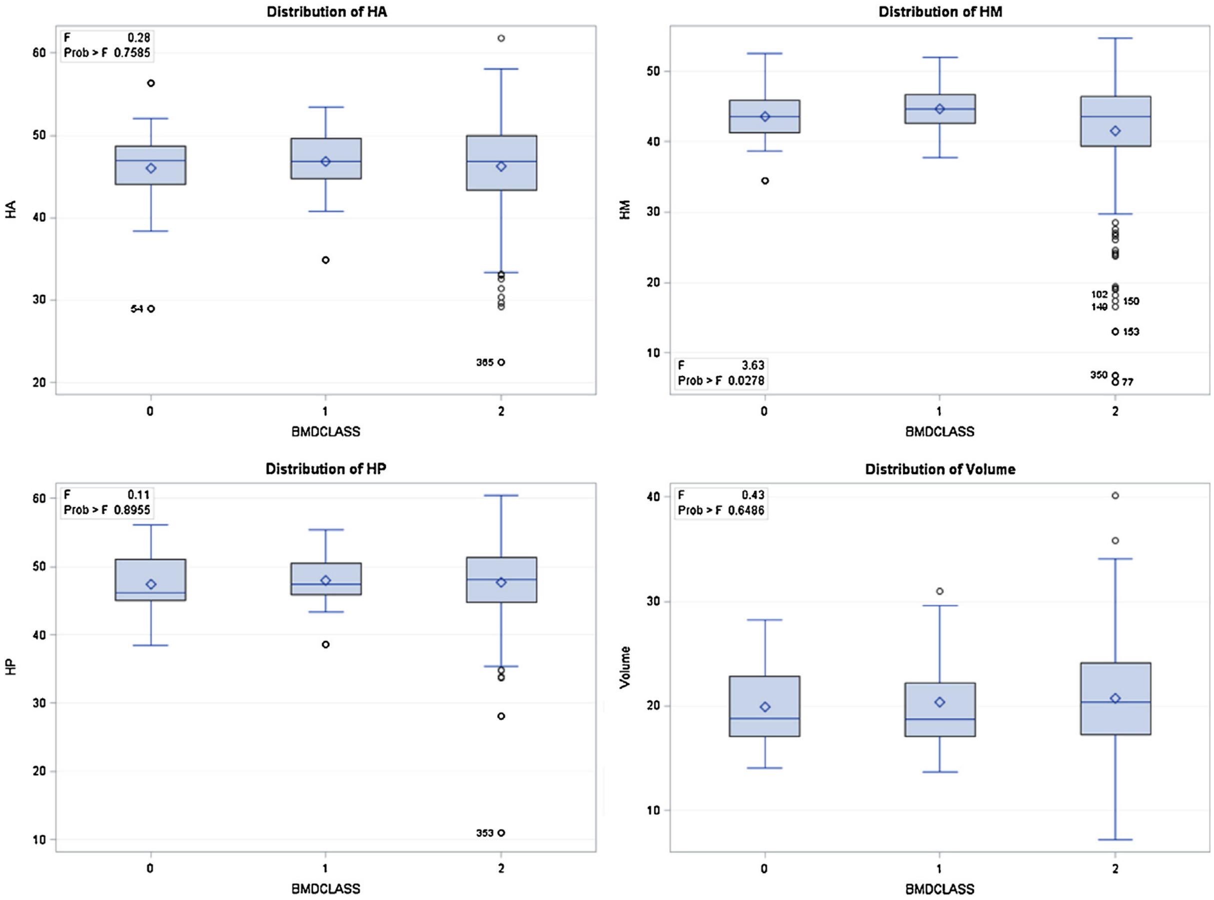
Graph 1 – Plots of all pairwise anterior (HA), middle (HM) and posterior (HP) vertebral heights and volume least-squares means differences for BMD groups (BMDCLASS) (0, 1, 2) at significance level 0.05.

which causes apparent tilting of vertebral bodies. Most at risk are those at the periphery of the image, where endplates appear as elliptical rims [37]. As for morphometry, the middle vertebral height measurement reliability becomes elusive [27]. Although MRI presents the highest accuracy in the evaluation of a vertebra [27,28]. During the study, only one case was equipped with the MRI examination only.

QCT is a single available technique that enables both morphometry and volumetry of the spine, combined with bone mineral density measurement. Other methods for bone mineral density assessment, such as DEXA, generate images, which are suitable for morphometry alone. Until recently, phantomless CT did not serve to measure BMD, although thorough analysis of vertebrae is available.

The results were compared with recent publications on the subject. The cardinal differences between the methods of calculating morphometric parameters exist. The used in this study software allows for semi-automated calculation, whereas the other authors, except one [30], relied on manual morphometry, either software-assisted [28] or not [29,31]. The limitation of this study is the lack of direct comparison of results with other studies because vertebral heights measurements were given in normalized pixels.

Abuzayed et al. [29] report on a characteristic pattern involving vertebral heights, where average anterior vertebral height increased from L1 to L5. However, the average anterior vertebral height was smallest at the L4 vertebra. In the current study, the anterior height increased from L1 (44.98 ± 3.77) to L3



Graph 2 – Differences of distribution of anterior (HA), middle (HM) and posterior (HP) heights and volume between BMD groups (BMDCLASS) (0, 1, 2).

(49.0 ± 3.9), followed by a drop at L4 (48.65 ± 5.25) and L5 (48.34 ± 4.87). The difference could represent the population itself since most of the vertebrae had decreased BMD values. Although, visually non-deformed vertebrae were used for comparison, there is a 20% margin of deformation possible [35]. Additionally, L5 vertebrae were represented most scarcely in our analysis. As for mean posterior vertebral height, our characteristics agree with the previous study [29]. Mean middle vertebral height followed the tendency reported on by Diacinti et al. [30], with an increase from L1 to L4. However, L5 cannot be discussed since the measurements concerning this level were missing.

A similar comparison was made with height ratios, derived from measured vertebral heights, providing an indirect method of juxtaposition. Wedge ratio (hA/hP), albeit slightly lower (range from L1 to L4 0.936–1.017 vs. 0.968–1.075), showed an increasing tendency across the lumbar spine, in accord with the above-mentioned study [30]. Analogically, biconcave ratio (hM/hP) tended to increase within a lower range (0.909–0.938 vs. 0.924–0.984). Again, data concerning L5 were unreported. The crush ratio was calculated (min[max[hPi/hPi − 1, hAi/hAi − 1], max[hPi/hPi + 1, hAi/hAi + 1]]) where hA is the anterior height of the vertebral body at the current level, hP is the posterior height of the vertebral body at the current level, hM is the middle height for the vertebral body at the current level, hPi − 1 is the posterior height of the vertebral body at the level below, hPi + 1 is the posterior height of the vertebral body at the level above, hAi − 1 is the anterior height of the vertebral body at the level below, and hAi + 1 is the anterior height of the vertebral body at the level above.

Karabekir et al. [31] analyzed vertebral morphometry of the Anatolian population and found, in contrast to our study, no significant differences between men and women regarding vertebral dimensions, apart from L1 anterior height. Mean values of selected vertebral dimensions were accordant with other studies. Individual variations among and within populations are a rule as documented in literatures [24–26,28–31].

Percutaneous minimally invasive spinal procedures, as vertebroplasty and balloon kyphoplasty, have been well established to address osteoporotic vertebral compression fractures [38]. Clinical and scientific experience shows analgesic values of bone cement to be independent of the volume used. Controversy exists over the amount of cement to be used in some fractures, i.e. fresh fractures, burst or osteoporotic fractures, where the cement has a crucial stabilizing function [38,39]. Some authors oppose the notion of filling the vertebral body completely. They believe the excess of the cement impedes bone healing or might lead to adjacent fractures since the elastic modulus of the treated vertebral body increases substantially. It was found that vertebral volume measurement is a valuable tool to assess the amount of bone cement to be used in pre-operative planning. Pre-operative planning is an established procedure in spinal surgery, being invaluable to the treatment success [40]. The volume of the vertebral body directly affects the amount of bone cement that could be injected during vertebroplasty. Height restoration and maintenance showed to be dependent on cement volume used [41].

Sagittal view morphometry remains a gold standard in the evaluation of vertebral fractures [24,25,34,35]. Vitrea 2 Workstation algorithm for volume measurement involves manual perimeter tracing of five slices in coronal view. A significant correlation between vertebral heights across the vertebral body and volume was noted. A relationship could be regarded as self-explanatory. Unlike anterior and middle heights, posterior height showed smaller Pearson correlation coefficient with vertebral body volume. Depending on the mechanism of trauma, accompanying spinal axial distortions, a vertebra could be affected on a single side. Vertebral volumetry would provide an additional insight into a deformed vertebra since single sagittal evaluation could underestimate the grade of deformation if it occurred peri sagittally and unilaterally. Thus, volumetry may serve as a complementary measurement for detailed shape analysis. Clinical implementation might be found not only in pre-operative planning but also patient monitoring, especially if combined with software-assisted analysis. Authors believe that relative time spent on manual tracing would be substantially reduced with new automated software and remains only a matter of time.

5. Conclusion

Morphometric parameters tended to be greater in males than in females, in a population of diversified bone mineral density. The most of measured vertebral dimensions differences between BMD groups were insignificant. It is postulated that upon placing different classification criteria in a more populous and diversified group a reliable pattern might reveal. BMD result should be considered as the modifying factor for preoperative planning of the bone cement volume to be deposited inside the vertebra.

Vertebral body volumetry might prove to be a useful tool in pre-operative planning as well as an alternative for treatment monitoring after minimally invasive spinal procedures.

Conflict of interest

None declared.

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Ethics

The work described in this article has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans; Uniform Requirements for manuscripts submitted to Biomedical journals.

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