Journal of Orthopaedics 49 (2024) 48–55

Contents lists available at ScienceDirect

Journal of Orthopaedics

journal homepage: www.elsevier.com/locate/jor

Interobserver variability in the determination of bone mineral density in Hounsfield units from differently configured fields of measurement in the cancellous bone of vertebral bodies from elderly body donors

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ARTICLE INFO

Keywords:
Hounsfield units
Interobserver variability
Bone density measurement
Bone mineral content measurement
Osteoporosis

ABSTRACT

Background: Due to the absence of suitable diagnostic procedures, osteoporosis (OP) is frequently detected late or not at all. Many elderly persons undergo computed tomographies (CT). The routine determination of Hounsfield units (HU) in bone as a part of these examinations could close a gap here.
Methods: Spines were extracted from 22 body donors, fixed in a PVC water phantom, and subjected to a high-resolution CT investigation. Cancellous bone was examined and its bone mineral density measured in HU from cervical vertebra 3 to lumbar vertebra 5 (484 vertebral bodies). On sagittal sections, a circular and a rectangular region of interest (ROI) were defined in mid-vertebral cancellous bone, positioned manually, and the measurements were performed by three experienced radiologists. Bone mineral density (BMD), measured in mg/cm^3, was used to determine the presence of OP.
Results: All of the spines were osteoporotic. In the presence of a BMD below 60 mg/cm^3 and HU values below 63.36 in lumbar vertebrae, there were significantly more vertebral body fractures in the thoracic and thoracolumbar spine. No difference was observed between the manually positioned circular and rectangular regions of interest (ROI) on the sagittal CT section ($p > 0.05$). Similar HU counts were obtained by the individual examiners ($p > 0.05$). The following formula was used to determine QCT values on a non-contrasted CT of the spine: $QCT = 0.6 \times HU + 13.7$.
Conclusions: Measurement of the density of cancellous bone in HU can be used to determine BMD for estimating demineralization. Quantitative BMD values in mg/cm^3, which can be calculated from the HU data, concur well with QCT values.

1. Introduction

Due to the unavailability of appropriate diagnostic procedures, osteoporosis (OP) is either diagnosed late or not at all.[1] Numerous computed tomography (CT) scans are performed in elderly persons for a variety of indications. Routine determination of the Hounsfield units (HU) of bone in the course of these investigations could close a gap here. The evaluation of bone density by means of a conversion formula could facilitate the diagnosis of OP and is therefore important, especially when preparing a patient for spinal surgery.

Fractures of vertebral bodies (VFs) constitute an economic and health-related burden, raise morbidity and mortality rates, and impair

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https://doi.org/10.1016/j.jor.2023.11.061
Received 14 November 2023; Accepted 22 November 2023
Available online 25 November 2023

quality of life.[2] Since many VFs tend to be clinically asymptomatic, imaging procedures play a vital role not merely after the onset of symptoms but also as a screening measure. Bone mineral density (BMD) expresses the stability of bone and is measured by various methods. The expression of BMD in HU would be a simple approach. Determination of the quality of bone is a decisive element of the success of treatment when preparing a patient for spinal surgery, and is also crucial for the prevention of an osteoporotic fracture.[3] The gold standard for determining the density of bone and identifying OP is dual energy X-ray absorptiometry (DXA).[4]

Evaluation of bone density in HU on a standard CT investigation could permit an estimation of BMD, improve diagnostic performance, and reduce unnecessary radiation exposure.[3] Bone mineral density is determined in HU on axial and sagittal CT sections. One either defines a round or an edge-following region of interest (ROI). Whether these procedures yield different HU counts has been scarcely investigated so far. Besides, we know little about interobserver variabilities in the measurement of HU. Determining HU in the various sections of the spine and their classification in accordance with bone loss in the spine, along with the accompanying risk of VFs, is as important as the creation and validation of a conversion formula to predict QCT values from HU. Based on HU measured in vertebrae, we intended to generate additional information about bone quality. For this purpose we investigated the CT-based morphology of individual sections of the spine, using spines obtained from 22 body donors. We focused on the following aspects:

1. Do HU differ in the various sections of the spine?
2. Do the determined HU correlate with QCT values of the lumbar spine (LS)?
3. Based on HU data, would it be possible to create a conversion formula for the estimation of QCT values?
4. Do the number of HU depend on the selected ROI?
5. Does any intra-observer variability exist for the variously positioned fields of measurement in the cancellous bone of vertebral bodies obtained from elderly body donors?

2. Methods

2.1. Study design and institutional board approval

The in vitro investigation conducted across multiple clinical centers received approval from the regional ethics committee of the Medical University (ethics committee vote A 2017-0072). All participants had previously consented to donate their bodies for scientific research during their lifetimes. Our procedures for obtaining human tissue for study were in accordance with the ethical standards outlined in the Declaration of Helsinki. Information regarding the donors' medical history was limited to the diagnoses mentioned on their death certificates. The bodies were categorized into groups based on the vertebral body location in the spine (CS, TS, LS).

2.2. Inclusion and exclusion criteria

Eligible body donors were required to be elderly and possess a set of 22 intact vertebral bodies. Exclusions from the study encompassed individuals with anatomical deformities, stunted growth, or severe bone conditions such as tumors, bone metastasis, Paget's disease, spinal fusion, scoliosis, block vertebrae, or those who had undergone spine surgeries involving the insertion of foreign materials.

2.3. Diagnostic imaging

Aligned with the natural anatomic features of the body, we extracted entire spines from 22 donated bodies. The spines were excised under non-aerated conditions and secured in a PVC water phantom (pipe made of unplasticized polyvinyl chloride or UPVC). The pipe, measuring 25 cm in diameter and 125 cm in length, served as the fixation medium (Fig. 1a).[5] Subsequently, we subjected the spines to examination using a high-resolution spiral CT device.

(GE Revolution EVO/64-slice CT/lateral scanogram, axial slice thickness <1 mm; the slice thickness of axial and sagittal reformations was 2 mm). In the sagittal reformations (Fig. 1b), deformities of the vertebral bodies were identified by three independent radiologists and graded to Genant et al.[6] Utilizing an external workstation (GE Healthcare AW Server®, Version 2.0), 3D volume rendering were generated to analyze the anatomy of the spine, with measurements conducted in GE Centricity RIS-i® Version 5.0.

2.4. Determination of Hounsfield units and bone density

In the CT investigation, the density of cancellous bone from CV 3 to LV 5 was determined in HU for 484 vertebral bodies, within a manually positioned ROI. The selected ROI was as large as possible; the vertebral cortex was excluded (Fig. 1c, d). On the sagittal section we defined a circular (SR) and an edge-following (SEF) ROI. For further calculation we determined the mean HU from the two values of the respective vertebral body and referred to this as the mean HU (MHU).

To evaluate intra-observer differences, the HU measurements of the circular and edge-following ROI were always performed by the same radiologist.

Furthermore, BMD was measured on a quantitative CT using a GE Revolution EVO computed tomography system and Mindways software. This was performed on the volume block at the level of LV 1, LV 2 and LV 3. Bone density was classified on the basis of averages expressed in mg/cm^3.

2.5. Statistics

The data analysis was carried out using SPSS (Version 23.0, Armonk, NY, USA). Parametric tests were employed to describe quantitative features. Means (M), standard deviation (SD) and the number (n) of observations were determined. These were displayed using the interval mean ± standard deviation (M±SD). Values obtained from non-parametric tests were shown as medians and the first and third quartiles (Q1-Q3). For comparisons between groups, we used the Kruskal-Wallis or the Mann-Whitney *U* test. The outcome of the Shapiro-Wilk test of normal distribution was employed to select the respective test. When the results were significant, we performed pairwise comparisons. Pearson's correlation coefficient (r) was calculated to describe correlations between two variables. A linear regression analysis was conducted to create a general formula for the calculation of QCT values. A Bland-Altmann plot was created to show the accuracy of the individual measurements in the two ROIs and their deviations from one another. For the Bland-Altmann plot we established a confidence interval of 95 %.

Statistical tests were two-sided to calculate p-values, with a significance level set at $p < 0.05$.

3. Results

The data derived from 484 vertebral bodies extracted from 22 human body donors were analyzed; seven of the donors were men and 15 were women. The donors' ages ranged from 66 to 102 years (mean age 81.1 ± 7.5 years). Four spines were excluded from further investigation due to metastases, advanced scoliosis, idiopathic skeletal hyperostosis, and a block vertebra. The overall average body mass index (BMI) was 22.6 ± 5.4 kg/m^2. All we knew about the donors' medical histories were the causes of their death. Table 1 summarizes medical histories, while Tables 2 and 3 show the frequency distributions of BMD and MHU from LV 1 to LV 3. OP was observed in all spines. Significantly more fusion fractures were found in the thoracic and thoracolumbar spine in persons with a BMD below 60 mg/cm^3. The most frequently affected vertebra in both men and women was LWK 1 with 9 Fs. The next in line were

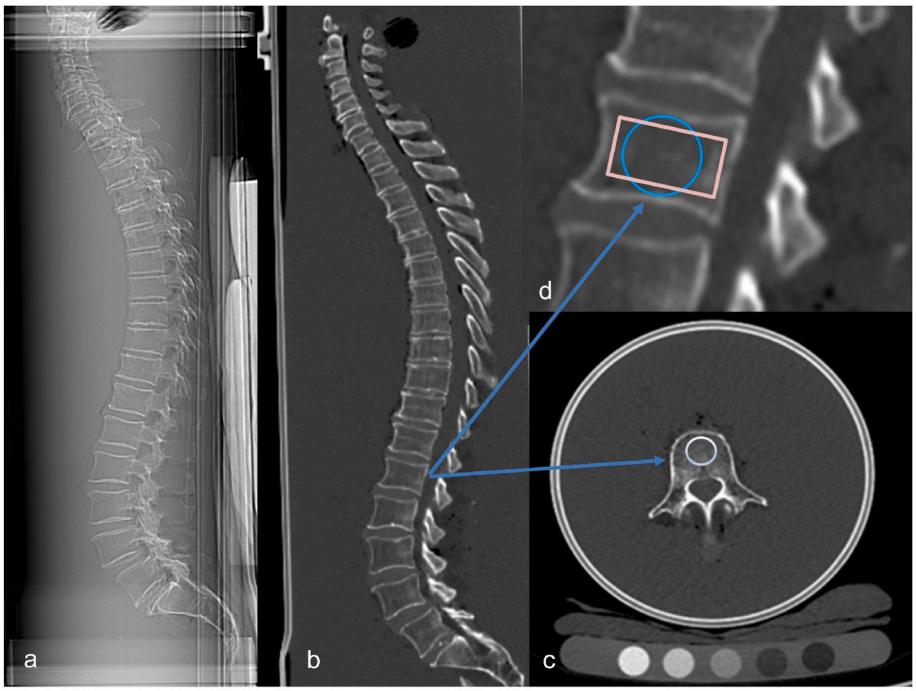

Fig. 1. a Experimental setup, image reformation and measurement of bone mineral density. Position of an embedded spine in a PVC water phantom: Lateral scanogram; **b** Sagittal CT section. For simulation of the soft tissue mantle, the spine was embedded, as far as possible in non-aerated condition, in water. **c** The transverse diameter of the phantom was 25 cm. To detect fractures we obtained a sagittal reconstruction, oriented as far as possible plane-parallel to the base and cover plates. d Within an individual sagittal, central, round and sagittal, elliptical, and irregular region of interest (ROI) in each vertebra in the spine, we determined bone density in HU (Hounsfield units). The above illustration shows L1 with a density of 68.9 HU in the circular and 70.1 HU in the rectangular ROI (**d**).

Table 1
Donor data.

	Overall group (n = 22)	Male (n = 7)	Female (n = 15)
Age (years)	81.1 ± 7.5	80.1 ± 6.1	81.6 ± 8.1
Gender (male/female)	7/15	9	17
Body mass index (kg/m^2)	22.6 ± 5.4	25.4 ± 5.4	21.3 ± 5.0
Extracted segments	C3-L5	C3-L5	C3-L5
Number of examined vertebral bodies (n)	484	154	330
Vertebral body fractures total (M ± SD)	1.9 ± 1.2	2.0 ± 1.5	1.8 ± 1.1
Affected vertebral bodies n (grade of severity according to Genant et al. 18)			
T5	1 (G1)		
T6	2 (1xG1, 1xG2)	1 (G2)	1 (G1)
T7	5 (4xG1, 1xG2)	2 (G1)	3 (2xG1, 1xG2)
T8	4 (1xG1, 3xG2)	2 (1xG1, 1xG2)	2 (2xG2)
T9	4 (3xG1, 1xG2)	2 (1xG1, 1xG2)	2 (2xG1)
T10	1 (G2)		1 (G2)
T11	1 (G3)		1 (G3)
T12	5 (3xG1, 1xG2, 1xG3)	3 (2xG1, 1xG2)	2 (1xG1, 1xG3)
L1	9 (5xG1, 4xG2)	3 (1xG1, 2xG2)	6 (4xG1, 2xG2)
L2	5 (3xG1, 2xG2)		5 (3xG1, 2xG2)
L3	1 (G2)		1 (G2)
L4	1 (G1)		1 (G1)

Variables expressed as mean ± standard deviation (M±SD) and number of observations (n).

thoracic vertebra (TV) 7 and TV 12 with 6 Fs each. In women, LV 1 had 6 observable Fs and was the most frequently affected vertebra. This was followed by LV 2 with 5 Fs, and TV 7 with 4 Fs. In male spines, TV 12 and LV 1 had 3 Fs each, and were thus the vertebrae most frequently affected by fractures. These were followed by TV 7, 8 and 9 with 2 Fs each. Above TV5, especially in the cervical spine, we found no Fs. VF were most commonly Grade 1 and 2 fractures according.

Table 2
Quantitative computed tomography (QCT) values for the different vertebrae (in mg/cm^3 K_2HPO_4).

	n	Minimum	Maximum	Mean
L 1	22	12.5	129.9	57.0
L 2	22	12.4	129.1	56.6
L 3	22	12.6	130.3	55.9
All levels	66	12.5	129.8	56.5

L, lumbar.

Table 3
Hounsfield units (HU) of the different vertebrae.

	n	Minimum	Maximum	Mean
L 1	22	23.0	317.0	78.0
L 2	22	13.2	199.8	73.8
L 3	22	14.3	165.2	66.0
All levels	66	16.8	212.4	72.6

L, lumbar.

Furthermore, we determined the density of cancellous bone in HU. In all of the investigated spines, cancellous bone was of much greater density in the cervical spine than in the thoracic or lumbar spine (Table 4). The distribution of the mid-vertebral density of cancellous bone over the entire spines showed a continuous increase in density as one proceeded towards the cervical vertebrae (Fig. 2). Independent of the defined ROI, the individual investigators achieved similar results (Fig. 3) (see Fig. 4).

MHU and QCT values revealed a high degree of correlation ($r = 0.914$, $p < 0.001$). Table 5 summarizes the outcome of the correlation

Table 4
Descriptive statistics of CT parameters.

Parameter	Group comparison[P]							
	Group	Total Median (Q1-Q3)	CS Median (Q1-Q3)	TS Median (Q1-Q3)	LS Median (Q1-Q3)	CS vs. TS p-value	CS vs. LS p-value	TS vs. LS p-value
Hounsfield units (Elevation with sagittal, central, round ROI)	Total	86.05 (72.85–134.53)	178.45 (150.73–186.27)	85.25 (75.33–102.26)	68.05 (64.14–73.14)	<0.001	<0.001	<0.001
Hounsfield units (Elevation with sagittal, edge-following, irregular ROI)	Total	90.61 (81.72–127.99)	181.62 (146.04–184.13)	90.61 (82.33–100.96)	66.76 (65.32–80.16)	0.013	<0.001	0.019

We present results as median, specifying the first and third quartiles (Q1-Q3) for non-normally distributed parameters.
CS, cervical spine; TS, thoracic spine; LS, lumbar spine; ROI, region of interest; P, pairwise comparison.

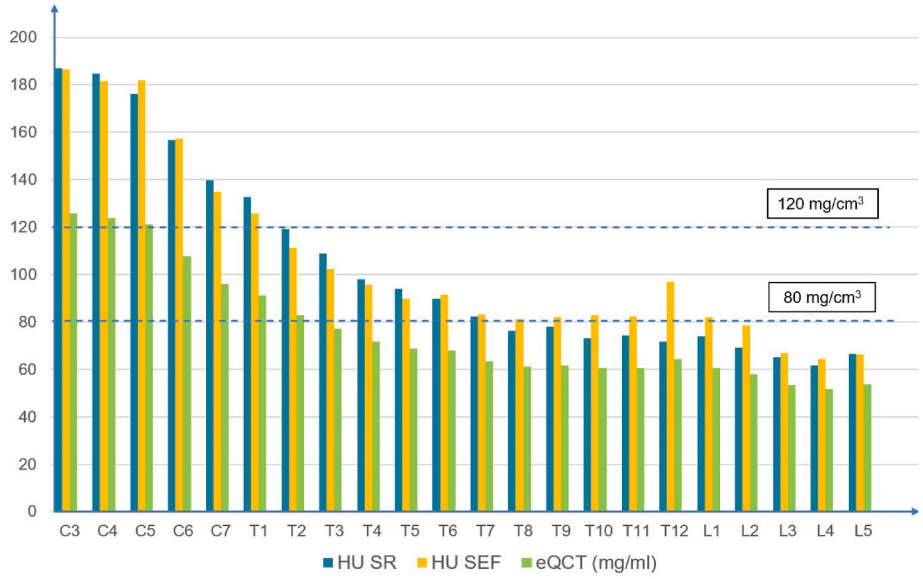

Fig. 2. Determined Hounsfield units (HU) depending on vertebral body level, with a sagittal, central, round (SR) and sagittal edge-following (SEF) region of interest. The estimated bone density values (eQCT) are shown with the reference ranges for normal bone mineral density (BMD >120 mg/ml) and osteoporosis (BMD <80 mg/ml) as defined by the American College of Radiology.

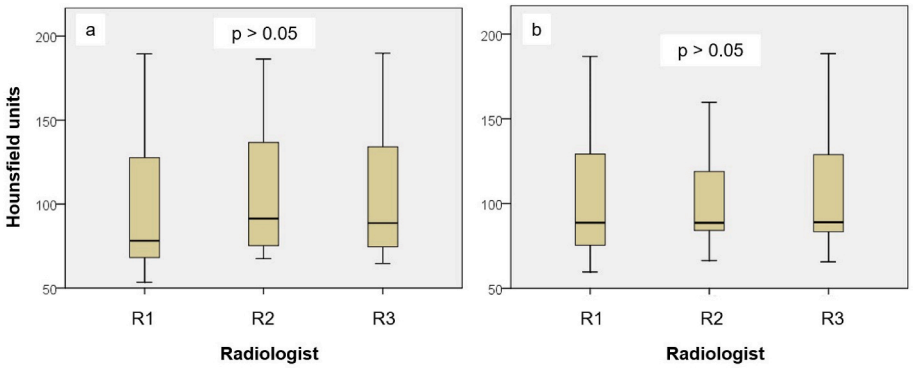

Fig. 3. Determined Hounsfield units in the entire spine by three independent radiologists (R1, R2, R3), depending on the survey pattern (**a**: survey with a sagittal, central, and round region of interest, **b**: survey with a sagittal, edge-following, and irregular region of interest) for 22 spines from CV 3 to LV 5.

analysis.

In order to investigate the concurrence between HU measurements in the sagittal plane, we formed a pair of differences from the variables: SR: sagittal round; SEF: sagittal edge-following). Then, in a Bland-Altman plot, the means of differences in HUs in the SR and SEF plane (M SRSEF) were calculated and plotted against the differences in HUs from the SR and SEF (Fig. 5). The graphical representation shows a mean value of −1.4 and the limits of the 2-fold standard deviation (2 SD). More than 95 % of the values are within these limits, which indicates that the SR measurement is not inferior to the SEF measurement, and that the two methods of measurement are equivalent.

In a regression analysis, the QCT value was estimated with the aid of a generalized estimating equation. The final formula was QCT value = 0.6 × HU + 13.7.

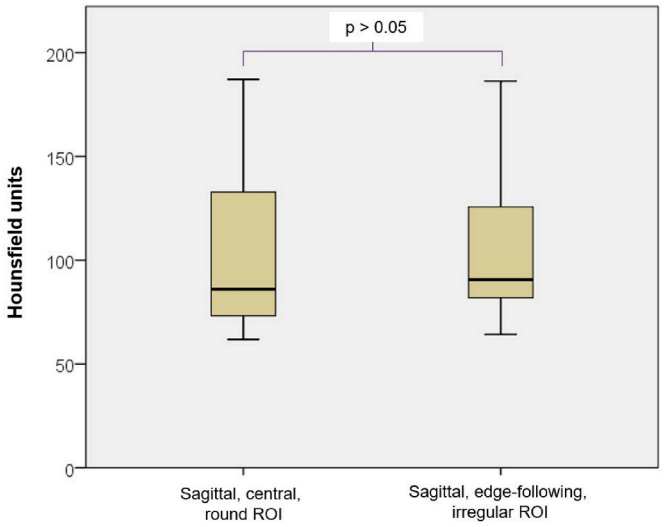

Fig. 4. Determined Hounsfield units in the entire spine, depending on the survey pattern, with a sagittal, central, round, or with a sagittal, elliptical, irregular region of interest for 22 spines from CV 3 to LV 5.

Table 5
Correlation between mean values of non-contrasted computed tomography (MHU) and the values of quantitative computed tomography (QCT) with the corresponding Pearson's® correlation coefficient in the individual vertebral bodies.

	n	Pearson's correlation (r)	P-value
L 1	22	0.837	<0.001
L 2	22	0.629	0.002
L 3	22	0.979	<0.001
All levels	66	0.914	<0.001

L, lumbar.

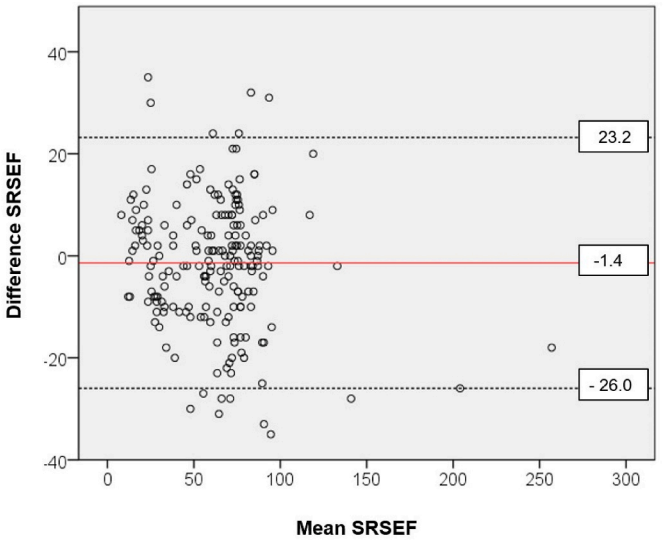

Fig. 5. Bland-Altman plot of the sagittal round (SR) and sagittal edge-following (SEF) pair: mean: 1.4; standard deviation 24.6, upper limit: SRSEF 23.2, lower limit: SRSEF -26.0).

4. Discussion

We were able to compare cancellous bone from all portions of spines, which were extracted from 22 aged body donors (age range, 66–102 years). The overall BMI was low normal. A BMI lower than 22 kg/m^2 is associated with a rising rate of fractures.[7] Associations between low body weight, a low body fat percentage, and a higher risk of fractures have been reported by many authors.[7,8] All investigated probands had bone mineral density values below 80 mg/cm^3 on bone densitometry, and therefore had osteoporosis.[9] At values below 60 mg/cm^3, all probands had fusion fractures.[10] The most important risk factor for these VFs was the advanced age of the probands. Fracture rates increase especially beyond the age of 70 years.[11] The VFs were typically distributed in the thoracolumbar and lumbar sections[12] (Table 1). The frequency of fractures in the cervical, thoracic and lumbar spine is an expression of the loads exerted on these sections. It may be assumed that local changes in microarchitecture and the function of the spine do exist and play a role in the frequency of fractures.[13–16]

The determination of HUs in the complete spine, including the corresponding BMD, has rarely been performed so far. HU serve as an index of the reducing intensity of the X-ray beam; the scale ranges from 1000 for air to 0 for water. The HU value of bone is typically between 300 and 3000 [17]. Hounsfield units permit conclusions about bone density. T-scores on dual X-ray absorptiometry (DXA) on the one hand and HU on the other, were reported to be significantly correlated in a single vertebral body (Schreiber et al.[17]).

Choi et al.[18] noted, in addition to a clear correlation between HU and T-scores in patients with degenerative spinal disease, the advantage of determining HU. HU is easily measured and serves as a convenient means of diagnosing OP in the course of frequent CT investigations.

OP is typically diagnosed on the basis of DXA measurements throughout the world. False high values may result from degenerative changes, osteophytes, osteochondrosis, scoliosis, and a potentially calcified aorta in front of the spine.[19,20] Besides, errors in positioning may lead to incorrect interpretation.[21] During follow-up measurements in patients undergoing treatment for OP, changes in overall DXA values at the hip and changes at the femoral neck were predictive of proximal femoral and vertebral body fractures. DXA measurements at the spine were predictive only for this site of measurement.[22] One must adopt a differentiated view: at least for vertebral bodies, the measurement of HU would serve as a useful option in clinical routine.

The HU value that could be used as a suitable threshold for proving osteoporosis is a subject of ongoing research. In patients with osteoporosis, Schreiber et al.[17] determined an average of 78.5 HU. At LV 1, while Buckens et al.[23] registered 99 HU. However, measuring HU at a single vertebral body may not permit conclusions about generalized bone degeneration and this approach must be viewed with caution. Accordingly, Scheyerer et al.[24] believe that HUs must be measured in at least three different lumbar vertebrae. According to the latter authors, the specific LV one selects for the measurement is not important. Rather, it is important that the vertebrae be devoid of degenerative (such as subchondral sclerosis), posttraumatic, or postoperative changes. In the present investigation, we determined HU at LV 1 to LV 3 to determine the presence of osteoporosis. The average value obtained for the entire group was 72.6 HU. Schwaiger et al.[25] noted that fractures occur more frequently below the level of 63.8 HU. This concurs with the results of our study. Furthermore, the HUs of the LS in women (on average 65.5 HU) were markedly below those in men (on average 87.9 HU), which could explain the more numerous fractures in women.[26]

A recently published overview concerning cut-off values of HU for the diagnosis of OP is worthy of mention.[27] A value below 136 HU in the LS should be given attention. The commonly used location for the determination of HU was the LS; we also have data concerning HU in the CS.[28] Colontonia[28] compared HU values in the CS with DXA measurements at the hip and reported threshold values for OP. This aspect is especially interesting. Recently, Rühling et al.[29] mentioned a cut-off value of 209.2 mg/cm^3 for OP at CV 4, and 83.8 mg/cm^3 for TV 12. We reported a complete series of HU measurements from C3 to L5 in a previous study.[30]

A further aim of the present study was to investigate the correlation

between QCT values and HU determined on a CT of the LS. For this purpose, we obtained the frequency distribution of bone density values on a QCT and HU determined on CT in the individual vertebral bodies from L1 to L3. These two variables were then compared and the correlation between the two was determined. The analysis revealed a very strong correlation between HU and the corresponding QCT values. Currently, we have a very small number of published studies concerning a potential correlation between HU on CT of the LS and QCT data. Baum et al.[31] reported a correlation between HU values on a contrast-enhanced CT of the abdomen and QCT values in 15 postmenopausal women aged on average 63 years. Müller et al.[32] showed, in their investigation of 82 patients aged on average 63 years, a strong correlation between HU and QCT values. Bauer and Henning[33] investigated 40 postmenopausal women aged on average 71 years, compared HUs in vertebral bodies on contrast-enhanced CT of the abdomen and the pelvis with QCT values in the LS, and also demonstrated a positive linear correlation.

Papadakis et al.[34] observed that CT data derived from routine MDCT investigations could be used to distinguish osteoporotic patients from healthy individuals. Buenger et al.[3] showed, in a study of 369 patients aged on average 67 years, a significant correlation between HUs and the corresponding QCT values. The latter were independent of the patient's sex. In the above mentioned studies,[3,31,33,34] the authors suggest a variety of equations to calculate QCT values from HU (Table 6). Our formula yielded somewhat lower BMD values than those reported in the above-mentioned studies. The advanced age of our body donors might serve as an explanation for this phenomenon. After completing their investigation of more than 5000 patients, Castillo-Lopez et al.[35] observed a reduction of 2 HU per year of life. It should be noted that the above-mentioned researchers used contrast media. The effects of contrast media, frequently used in the clinical setting for obtaining CT scans, on the measurement of BMD and on fracture risk are a debated issue.[36] Depending on the patient's age, the trabecular network is vascularized to a greater or lesser extent. Vascularization of the vertebral bodies is better in younger patients, whereas older individuals usually have fatty vertebrae.[3] The HU value is mainly dependent on blood circulation, the time of contrast application, the contrast phase of the CT investigation, and the vascularization of the respective tissue.[3] In our investigation, we only used non-contrasted CT investigations, as this is much more frequent in clinical routine than computed tomography scans with contrast media. Only Buenger et al.[3] employed non-contrasted CT as we did in the present investigation. As regards the method of measuring HU, several approaches have been used so far. In the cancellous bone of vertebrae, some authors determined HU on the axial section.[37] Others determined HU on sagittal sections of the CT scan.[25] However, there were no differences in validity.

Felsenberg et al.[38] registered a mean deviation of 2.5 % for elliptical, circular, rectangular and freely determined ROIs in homogeneous cancellous bone with normal BMD. A much greater dispersion of 9 % was observed in the presence of inhomogeneous osteoporotic trabecular bone.[38]

Table 6
Conversion formulas reported in previous studies.

Authors	Formula	Use of contrast enhancement Yes/No
Bauer et al., 2007	QCT value = 0.96 × HU – 20.9	Yes
Papadakis et al., 2009	QCT value = 0.78 × HU + 10.13	Yes
Baum et al., 2012	QCT value = 0.695 × HU – 7.9	Yes
Bünger et al., 2021	QCT value = 0.7 × HU + 17.8	No
This study	QCT value = 0.6 × HU + 13.7	No

HU: Hounsfield Unit; QCT: quantitative computed tomography.

In the present investigation, a circular ROI was compared to an edge-following ROI on sagittal sections. We registered no difference in the HUs determined for these ROIs. Interestingly, a number of investigators achieved similar results. The assessment of sagittal sections alone in regard of VFs and trabecular bone mineral density on routine CT investigations of the abdomen offers, according to Lee et al.,[39] a rapid and effective means of screening and identifying patients at high risk of fragility fractures. The authors studied 571 persons aged on average 71 years. As in our study, the sagittal reconstruction was investigated in regard of moderate to severe VFs using Genant's[6] visual semi-quantitative assessment. OP was considered likely in persons with moderate to severe VFs and/or a trabecular LV 1 attenuation of ≤110 HU on the sagittal view. In a study performed in the United Kingdom[40] comprising 536 patients aged on average 66 years, who underwent a CT of the abdomen and a DXA investigation within one year, the authors determined a threshold of 104 HU for OP. Independent of the patient's sex, we registered 78 HU for LV 1 in the present study.

The determination of HU in the spine influences the assessment of complications after spinal surgery as well. According to Li et al.,[41] HUs serve to predict screw loosening better than any other method. The latter authors believe that loosening can be minimized by creating an optimum trajectory for the screw on the basis of HU determined on the preoperative CT.

Finally, it may be stated that the routine procedure of a CT of the abdomen with no additional costs or radiation exposure can be utilized as an opportunistic screening method for OP. We obtained similar values as those reported in the past for other populations[40,42]

4.1. Conclusion for clinical practice

The risk of fractures increases in direct proportion to the reduction of bone mineral density in cancellous bone[10]; the same was observed in the spines investigated for the present report. However, in the cervical spine, even overt osteoporosis does not favor the occurrence of fusion fractures in cancellous bone.

In cases of clinically suspected osteopenia/osteoporosis, the additional measurement of the density (HU) of cancellous bone in the spine on CT scans of the chest and abdomen provides valuable information.

The present study revealed a significant correlation between HUs measured on non-contrasted CTs of the LS and the corresponding QCT values. HUs correlate in linear fashion with QCT values. The conversion formula for the estimation of QCT values from HU permits the assessment of bone quality. The treating surgeon may integrate this information into his/her preoperative preparation. This approach permits exact preoperative planning and prevents potential postoperative complications. This screening method avoids additional radiation exposure and reduces examination time for the patient. Opportunistic screening can be performed, VFs identified, and BMD can be measured on routine CT scans. However, the techniques must be integrated into the clinical work process and also need to be validated further in regard of the prediction of fracture risk.[36]

4.2. Limitations

The study material was limited to the available body donors. Complex statistical procedures could not be employed for this descriptive study due to the limitations in the data. The samples investigated were exclusively derived from elderly individuals who had donated their bodies for scientific research during their lifetimes. Conclusions regarding younger individuals cannot be drawn from these data. The medical histories of the donated bodies were largely unknown, including information about the types of drugs used, the duration of treatment, or physical therapy for osteoporosis.

Compliance with ethical standards

The ethical standards of the Declaration of Helsinki were followed in the methods used to extract human tissue.

Trial registration

The regional ethics committee of the Medical University (approval number A 2017-0072) approved this multicenter clinical in vitro investigation.

Informed consent

All probands were either members of the body donor program at the department of anatomy, or autopsied specimens were obtained from the Medical University Institute of Forensic Medicine. The body donors had donated their bodies to scientific research after their death.

Funding source

The authors explain that there was no funding source.

Guardian/patient's consent

All body donors were in the University Medicine program and gave their consent during their lifetime to make their bodies available to science after their death.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgements

The authors sincerely thank those who donated their bodies to science and their gesture in promoting anatomical research. Results from such research could potentially enhance our overall knowledge and thus improve patient care. We express our utmost gratitude to these donors and their families.

Abbreviations

BMD	bone mineral content
BMI	body mass index
cm	centimeter
CS	cervical spine
CT	computed tomography
CV	cervical vertebra
DXA	dual X-ray absorptiometry
Fig	Figure
G	grade
g/cm^3	gram/cubic centimeter
HU	Hounsfield units
kV	kilovolt
kg	kilogram
LV	lumbar vertebra
LS	lumbar spine
M	mean value
MDCT	multi-detector computed tomography
mg/cm^3	milligram/cubic centimeter
Micro-CT	micro-computed tomography
ml	milliliter
mm	millimeter
n	number
OP	osteoporosis
QCT	quantitative computed tomography
ROI	region of interest
SD	standard deviation
SR	sagittal round
SEF	sagittal edge-following
TS	thoracic spine
TV	thoracic vertebra
VFs	vertebral fractures

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