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Exploring the impact of body mass index on the accuracy of vertebral bone quality in determining bone mineral density in patients undergoing lumbar fusion surgery

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Abstract

Objective To investigate whether body mass index (BMI) affects the accuracy of vertebral bone quality (VBQ) in determining bone mineral density (BMD) in patients undergoing lumbar fusion surgery.

Methods In this retrospective study, patients with preoperative noncontrast T1-weighted MRI were included. Restricted Cubic Spline (RCS) was employed to explore the nonlinear relationship between BMI and VBQ. Then patients were stratified according to the threshold of BMI. Pearson correlation analysis and linear regression were used to analyze the correlation between VBQ and the BMD in different groups. Receiver operating characteristic (ROC) analysis to calculate the area under the curve (AUC) was used to assess diagnostic efficacy according to BMI.

Results A total of 328 patients (201 female and 127 male patients) with a mean age of 68.3 ± 3.3 years were included in the study. Significant nonlinear relationship was observed given the results of RCS. In patients with BMI < 23.8 kg/m^2, the correlation coefficient between VBQ and the lowest BMD was − 0.32 and significant distribution difference of VBQ score was observed between osteoporosis and normal as well as osteopenia subgroups. However, in patients with BMI ≥ 23.8 kg/m^2, the correlation coefficient between VBQ and the lowest BMD was − 0.39 and significant distribution difference of VBQ score was observed in all three subgroups. In addition, the ROC analysis revealed that the predictive performance in determining low BMD was superior in patients with BMI ≥ 23.8 kg/m^2 (AUC 0.80 vs. AUC 0.66, $p = 0.034$).

Conclusions In this study, significant nonlinear relationship between BMI and VBQ was observed. Compared with patients with BMI < 23.8 kg/m^2, VBQ has better discrimination between higher BMI (≥ 23.8 kg/m^2) patients with low BMD and those with normal bone density.

Keywords Vertebral bone quality, Bone mineral density, Osteoporosis, Degenerative, Lumbar

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Introduction

Osteoporosis is a systemic skeletal metabolic disorder characterized by a low bone mass density (BMD) and microarchitectural deterioration of bone tissue, with an increased risk of fragility fractures [1–3]. With an increasingly aging population, managing degenerative spinal diseases combined with osteoporosis has become a challenge for spine surgeons [4]. Evidences suggested that the prevalence of osteoporosis in patients (>50 years) undergoing lumbar fusion surgery were 48.9% in female and 27.1% in male, respectively [5]. Patients with osteoporosis who undergo lumbar fusion surgery are more prone to experience postoperative complication than their normal BMD counterparts [6–8]. Therefore, accurately identifying patients with osteoporosis preoperatively and giving appropriate measures (such as the use of bone cement screws) during surgery will reduce the occurrence of postoperative mechanical complications.

Dual-energy x-ray absorptiometry (DEXA) remains the gold standard for assessing bone quality [9]. However, osteophytes, coronal or sagittal deformity and aortic calcification dramatically increase the risk of false negatives, which limits the reliability of DEXA [10, 11]. Therefore, a simple, accurate and complementary method that can evaluate BMD by preoperative routine imaging is still needed in clinical practice. Based on noncontrast, T1-weighted MR, vertebral bone quality (VBQ) score is a new technique to evaluate bone quality, and its principle is to measure the fat content of the vertebra and indirectly reflect the bone quality [12]. However, many patient-specific variables affect the diagnostic efficacy, such as age, gender and hyperlipidemia [9, 13, 14]. In addition, since osteoblasts and adipocytes are differentiated from mesenchymal stem cells, a higher body mass index (BMI) can stimulate the development of mesenchymal stem cells into adipocytes, which may affect the accuracy of VBQ in determining bone quality [15–17]. Therefore, this study aims to (i) investigate whether BMI affects the accuracy of VBQ in determining bone quality and (ii) how does BMI affect the accuracy of VBQ in determining bone mineral density in patients undergoing lumbar fusion surgery.

Methods

Study design and participants

The study was conducted after obtaining approval from the ethics committee (IRB#2018086) of our hospital. This study was retrospective and the study did not contain information that could identify the patients, therefore, written and signed informed consent was waived. Consecutive older patients (>65 years) who underwent lumbar fusion surgery for degenerative lumbar conditions with available preoperative DEXA and lumbar T1-weighted MRI between January 2020 and July 2023 were included in the study. Exclusion criteria were as follows: (1) patients with previous lumbar instrumentation; (2) patients who underwent surgery for lumbar infection, lumbar vertebral fracture and primary or secondary spinal tumor; (3) patients with severe spinal deformity or multilevel lumbar spinal stenosis than making VBQ assessment impractical. The demographic and medical characteristics included age, gender, BMI, smoker, drinker, hypertension, diabetes and hyperlipidemia were enrolled. In addition, laboratory variables included triglycerides, total cholesterol, calcium and phosphate.

VBQ measurement

T1-weighted non-contrast lumbar MRI studies were obtained using 3.0 Tesla Trio Tim scanners (Siemens, Erlangen, Germany). The standard scanning protocol included a field of view (FOV) of 310 * 310 mm, a matrix size of 320 * 320, a repetition time (TR) / echo time (TE) of 550 ms / 9.6 ms, 11 slices per slab, a slice thickness of 4.0 mm, and 2 excitations (NEX) for sagittal T1-weighted scans. The region was positioned with the trabecular bone of the L1-L4 vertebrae and the ventral cerebral spinal fluid (CSF) posterior to the L3 vertebra on the midsagittal plane. In the case of poor visibility of the median sagittal plane slice, the parasagittal plane was served as an alternative to assess VBQ. For patients with spinal stenosis at the L3 level, CSF at the adjacent-segment level was utilized for measurements. The mean signal intensity (SI) at vertebrae and CSF were recorded. The VBQ score was calculated by taking the median SI of the L1–L4 vertebrae divided by the SI of the L3 CSF according to previous published study [5, 18]. All the VBQ were measured by picture archiving and communication systems (PACS). The VBQ score was measured by a trained resident doctor Q.J.W. who was blinded to DEXA T values. To evaluate the intra- and interobserver reliability, repeat measurement in 30 randomly selected patients were performed by Q.J.W. and P.W. by 2 weeks interval.

DEXA results

DEXA data were collected from the patient's medical records. DEXA scans were performed on the lumbar spine (L1-L4), femoral neck and total hip. BMD was classified as normal ($T \geq -1.0$), osteopenia ($-1 > T > -2.5$) and osteoporosis ($T \leq -2.5$) according to WHO criteria based on the lowest T value of the abovementioned anatomical sites.

Statistical analysis

Histograms and Shapiro-Wilk test were used to evaluate the distribution of numerical variables. Continuous variables were represented by mean and standard deviation (SD) if normally distributed; otherwise, median and interquartile (IQR) were used. Continuous variables with

a normal distribution were analyzed using two-samples t test, if not, Wilcoxon rank sum test was performed. The frequency and percentage were used to report categorical variables, and chi-square or Fisher's exact tests were employed to determine the difference. In order to investigate whether BMI affects the accuracy of VBQ in determining bone quality, a Restricted Cubic Spline (RCS) was employed and adjusted by all covariables. Akaike information criterion (AIC) was used to determine appropriate knots. Finally, the RCS with 3 knots and used a reference value of 23.8 kg/m^2 to categorize patients into two groups. Pearson correlation analysis and linear regression were used to analyze the correlation between VBQ and the BMD in different groups. The comparison of diagnostic scores among BMD subgroups was analyzed using one-way ANOVA. Receiver operating characteristic (ROC) analysis to calculate the area under the curve (AUC) was used to assess diagnostic efficacy. All the analyses were performed using R software (version R-4.3.3) with statistical significance set at $p<0.05$.

Results

Demographic

A total of 328 patients (201 female and 127 male patients) with a mean age of 68.3±3.3 years were included in the study. The mean BMI was 25.7±3.58 kg/m^2. There were 58 patients (17.7%) with current smoker and 43 patients (13.1%) with current drinker, respectively. Regarding medical comorbidities, 173 patients (52.7%) with hypertension, 83 patients (25.3%) with diabetes, 155 patients (47.3%) with hyperlipidemia and 104 patients (31.7%) with normal BMD. In addition, the total average triglyceride of 1.58 mmol/L, total cholesterol of 4.93mmol/L, calcium of 2.26mmol/L and phosphate of 1.21 mmol/L. The detail information was summarized in Table 1.

Table 1 Demographics, comorbidities and laboratory variables of included patients

Characteristics	Total ($n=328$)
Demographics	
Age (yrs)	68.3±3.3
Female, n (%)	201 (61.3%)
BMI (kg/m^2)	25.7±3.58
Current smoker, n (%)	58 (17.7%)
Current drinker, n (%)	43 (13.1%)
Medical comorbidities	
Hypertension, n (%)	173 (52.7%)
Diabetes, n (%)	83 (25.3%)
Hyperlipidemia, n (%)	155 (47.3%)
Normal BMD, n (%)	104 (31.7%)
Laboratory index	
Triglyceride (mmol/L)	1.58±0.86
Total cholesterol (mmol/L)	4.93±1.01
Calcium (mmol/L)	2.26±0.13
Phosphate (mmol/L)	1.21±0.15

RCS between BMI and VBQ

Both the intra- and interobserver reliability were excellent (≥0.8). Significant nonlinear relationship was observed given the results of RCS with 3 knots (Fig. 1). VBQ decreases with the increase of BMI before exceeding the reference value (23.8 kg/m^2) but increases after exceeding the reference value. After categorized according to the reference value, there was no significant difference in all characteristics among groups (Table 2).

BMI-related distribution of BMD

One-way ANOVA post hoc test indicated that in patients with BMI<23.8 kg/m^2, there were significant difference in VBQ between normal and osteoporosis group and between the osteopenia and osteoporosis groups, with no significant difference between the normal and osteopenia groups. In contrast, in patients with BMI≥23.8 kg/m^2, there was a significant difference between the two comparisons in all three subgroups, with VBQ values increasing with lower BMD (Fig. 2).

Correlations between VBQ and BMD T scores by BMI

The correlation between the VBQ and BMD T score was shown in Fig. 3. Significant negative relationship was observed both in patients with BMI<23.8 kg/m^2 (correlation coefficient was −0.32, adjusted R^2 was 0.103, $p<0.001$) and BMI≥23.8 kg/m^2 (correlation coefficient was −0.39, adjusted R^2 was 0.153, $p<0.001$).

Diagnostic accuracy by BMI

There was significant worse diagnostic accuracy in determining BMD based on VBQ in patients with BMI<23.8 kg/m^2 than patients with BMI≥23.8 kg/m^2 (AUC 0.80 vs. 0.66, $p=0.034$). The cut-off value was 3.04 with sensitivity of 74.4% and specificity of 45.6% in patients with BMI<23.8 kg/m^2 and 3.18 with sensitivity of 86.7% and specificity of 60.1% in patients with BMI≥23.8 kg/m^2. In addition, the AUC in total patients was 0.74 with cut-off of 3.15, sensitivity of 84.5% and specificity of 58.3. The detailed characteristics were summarized in Fig. 4; Table 3.

Discussion

In this study, intricated relationship between BMI and VBQ were identified. Further the impact of BMI on the diagnostic accuracy of the VBQ for assessing BMD was explored, and we found better performance in patients with BMI≥23.8 kg/m^2.

As an osteoporosis screening tool, VBQ score gains more attention in degenerative lumbar conditions [6, 7, 19]. In a retrospective cohort study, Ehresman et al.,

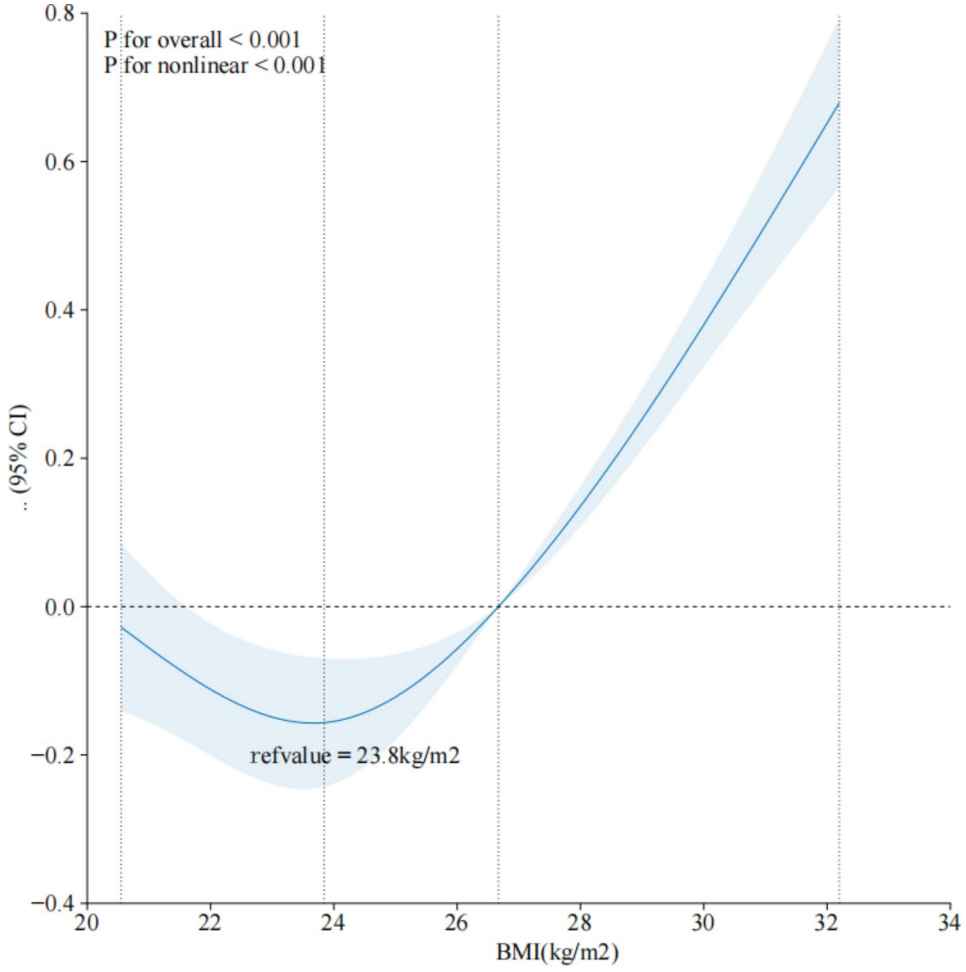

Fig. 1 The result of nonlinear relationship between BMI and VBQ evaluated with restricted cubic spline curve

Table 2 Demographics, comorbidities and laboratory variables based on BMI cut-off

Characteristics	BMI < 23.8 kg/m² *n* = 115	BMI ≥ 23.8 kg/m² *n* = 213	*p* value
Demographics			
Age (yrs)	67.9 ± 3.1	69.1 ± 3.4	0.064
Female, n (%)	65 (56.5%)	136 (63.8%)	0.194
Current smoker, n (%)	24 (20.9%)	34 (16.0%)	0.266
Current drinker, n (%)	18 (15.7%)	25 (11.7%)	0.316
Medical comorbidities			
Hypertension, n (%)	64 (55.7%)	109 (51.2%)	0.534
Diabetes, n (%)	30 (26.1%)	53 (24.9%)	0.811
Hyperlipidemia, n (%)	61 (53.0%)	94 (44.1%)	0.106
Normal BMD, n (%)	39 (33.9%)	65 (30.5%)	0.528
Laboratory index			
Triglyceride (mmol/L)	1.51 ± 0.75	1.65 ± 0.91	0.072
Total cholesterol (mmol/L)	4.73 ± 0.91	4.99 ± 1.04	0.087
Calcium (mmol/L)	2.26 ± 0.11	2.27 ± 0.13	0.458
Phosphate (mmol/L)	1.11 ± 0.13	1.23 ± 0.17	0.101

indicated that VBQ score to be a significant predictor of healthy versus osteopenia/osteoporosis with an accuracy of 81% [18]. A recent study conducted by Pu et al., they indicated that VBQ could achieve accurate cage subsidence prediction in patients following oblique lumbar interbody fusion [6]. In addition, in a recent study, Li et al., demonstrated that VBQ stands as a comprehensive index reflecting the quality of bone and the severity of paravertebral muscle degeneration [12]. All of these studies showed tremendous promise for evaluation of bone health with VBQ in spine patients.

However, present literature has many limitations in the clinical application and interpretation of the VBQ values. Contrast to DEXA and CT HU, which assess BMD mainly rely on inorganic components, obtained using T1-weighted images from MRI, VBQ score was calculated based on the principle that T1 signals reflect the degree of fatty infiltration of the vertebrae [14]. In addition, prior studies have shown high VBQ score values to correlate with BMD T-scores and predict fragility fractures independent of DEXA [5]. These findings suggest

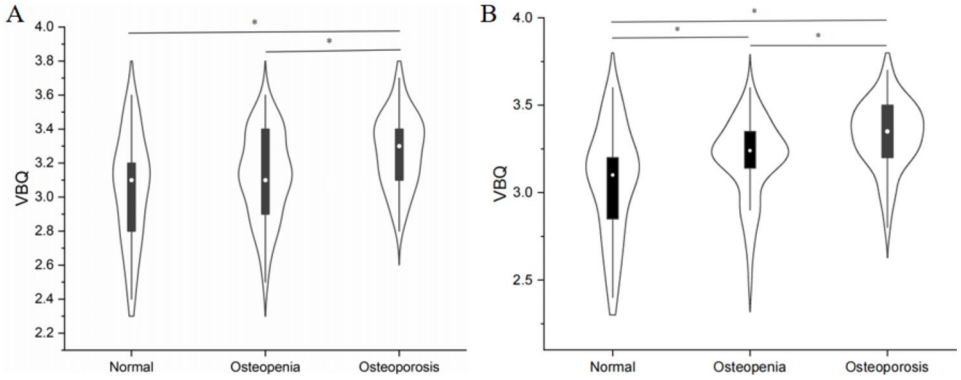

Fig. 2 The violin plot combined with box plot to demonstrate the VBQ score distribution among different diagnostic subgroups, separated by BMI (Fig. 2A indicates patients with BMI < 23.8 kg/m^2, Fig. 2B indicates patients with BMI ≥ 23.8 kg/m^2). *$p < 0.05$

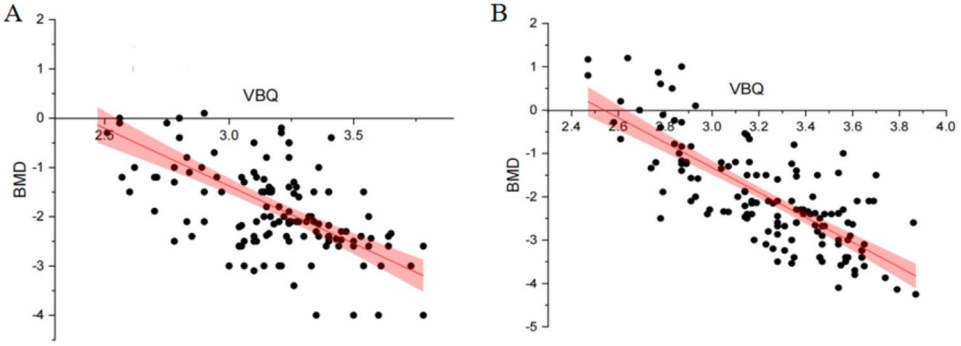

Fig. 3 Correlation between VBQ score and lowest T-score on DEXA scans (patients with BMI < 23.8 kg/m^2, $r = -0.32$, adjusted $R^2 = 0.103$, $p < 0.001$) (Fig. 3A); patients with BMI ≥ 23.8 kg/m^2, $r = -0.39$, adjusted $R^2 = 0.153$, $p < 0.001$) (Fig. 3B)

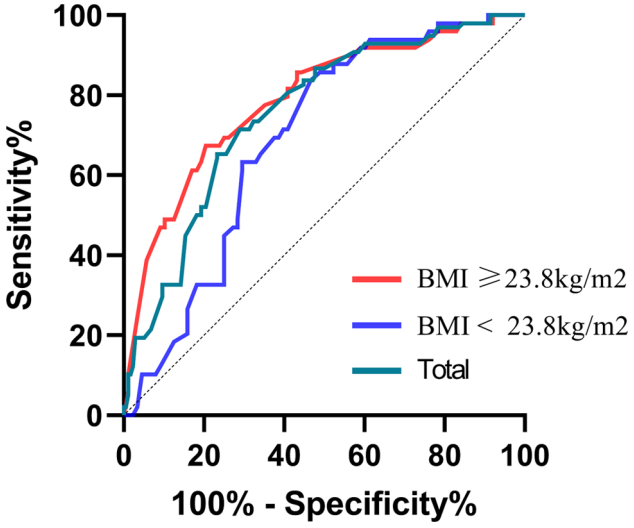

Fig. 4 ROC curves of VBQ score in the diagnosis of osteopenia/osteoporosis in patients with BMI < 23.8 kg/m^2 (AUC 0.66), and patients with BMI ≥ 23.8 kg/m^2 (AUC 0.80) and in all patients (AUC 0.74)

Table 3 Accuracy of VBQ in determining osteoporosis based on BMI cut-off adjusted for other covariates

	Cut-off	Sensitivity	Specificity	AUC	*p* value
BMI < 23.8 kg/m^2	3.04	74.4	45.6	0.66	< 0.001
BMI ≥ 23.8 kg/m^2	3.18	86.7	60.1	0.80	< 0.001
Total	3.15	84.5	58.3	0.74	< 0.001

there may be factors that influence the VBQ score which make it a more sensitive predictive tool than DEXA. In a retrospective study, Liu et al., found that the VBQ score was positively correlated with age, and notable increase in bone loss as measure by VBQ score occurred after 50 years old [13]. Wang et al., indicated that sex difference significantly affects the accuracy of VBQ score assessing bone density in patients undergoing lumbar fusion surgery [9]. The correlation between VBQ score and BMD T value in female patients was higher than that in male patients, which may be due to that the VBQ score reflects the degree of vertebral fat infiltration and after postmenopause, the fat content in the bone marrow cavity increases, and the change of bone marrow fat content may be more rapid than that of men. In addition, Aynaszyan et al., indicates that hyperlipidemia leads to falsely elevated VBQ score in patients with normal BMD [14]. In our study, we found that BMI exerts complicated role in VBQ measurement. VBQ decreases with the increase of BMI before exceeding 23.8 kg/m^2, but increases after exceeding the reference value. The mechanism of the phenomenon remains unknown but likely to

be multifactorial. One hypothesis holds that increased static mechanical compliance due to BMI accumulation causes the axial static mechanical pressure and changes in bone structure [20–22], which makes the bone stronger and simultaneously accompanies with lower VBQ. However, since osteoblasts and adipocytes are differentiated from mesenchymal stem cells, obesity can stimulate the development of mesenchymal stem cells into adipocytes [22–24]. Inappropriate accumulation of bone marrow adipocytes in the skeletal can lead to an imbalance in osteocyte activity and a reduction in bone turnover [24]. In addition, the proliferation of adipocytes in the microenvironment of bone marrow will hasten the release of pro-inflammatory and immunoregulatory substances, which accelerates the production and activation of osteoclasts, while diminishing the differentiation of osteoblasts, and inducing osteoclasts [2, 25, 26].

To the best of our knowledge, this is the first study with relative large sample to explore the impact of BMI on the accuracy of VBQ assessing bone density in patients with degenerative spinal conditions. In a study to explore the impact of patient physiology on VBQ score [14], significant higher VBQ score was observed in osteoporotic patients with higher BMI (>30 kg/m^2), but the results of univariate and multivariate backward linear regression did not identify BMI as a contributor to VBQ, which may be due to the limited sample size (a total of 156 patients). In addition, the results of this study demonstrated that the diagnostic power of VBQ for BMD in patients with BMI≥23.8 kg/m^2 was excellent according to trapezoidal rule with a threshold of 3.18. The threshold was significantly differed from previous studies, with a relative small sample size (130 patients with only 19 male patients and 111 female patients) at a threshold of 2.7 [27] and another research with a sample of mainly Caucasians at a threshold of 2.388 [28]. Therefore, race may exert potential role in determining the accuracy of VBQ assessing BMD. The inconsistent results suggest that the influence of patient-specific variables remains to be studied, and more research is needed to adjust and optimize its calculation and application guidelines. Therefore, VBQ score should be treated as a primary screening tool for an opportunistic assessment of BMD rather than a replacement for QCT or DEXA due to its indirect indicator properties in the current period [9].

The study had several limitations. Most importantly, patients were studied retrospectively from a single center, all included patients were Chinese and there existing a selection bias in the region, which limiting the generalizability of current findings. In addition, the study only investigated the impact of BMI on the VBQ in determining BMD. Whether sex impacts VBQ in predicting fragility fractures and osteoporosis-related complications needs further investigation. Last, despite that the science under the VBQ method is robust and numerous studies from different institutions have demonstrated its usefulness, it should be noted that the method could be an opportunistic screening method or complementary assessment due to its simplicity and economic efficiency, but it could not replace the DEXA scan at current stage.

Conclusion

The accuracy of VBQ, an emerging bone density assessment method, to diagnose low BMD is affected by BMI, with better performance in patients with higher BMI. A multicenter, multiracial, prospective study is needed to corroborate its clinical value.

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Author contributions

S.B.L., C.K., and P.W. were responsible for the concept and experimental design. X.Z. performed the data analysis and statistical analysis. Q.J.W. provided technical and material support. S.B.L., X.Z., and C.K. were involved in drafting and revision of the manuscript. S.B.L. and P.W. supervised this study. All authors discussed the results and commented on the manuscript.

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Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent for publication

The current study did not include images that could identify patient information and all participants signed informed consent regarding publishing their data to the journal.

Ethical statement

The study protocol was validated by the institutional review board in Xuanwu Hospital Capital Medical University (IRB#2018086). A written informed consent was obtained from all the participants in this study.

Competing interests

The authors declare no competing interests.

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