



Diagnostic value of a magnetic resonance imaging (MRI)-based vertebral bone quality score for bone mineral density assessment: an updated systematic review and meta-analysis

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Background: Many studies have explored the application of the magnetic resonance imaging (MRI)-based vertebral bone quality (VBQ) score as a tool for opportunistic osteoporosis screening before spine surgery. We aimed to conduct a systematic review and meta-analysis of studies to determine the diagnostic value of the VBQ score for bone mineral density (BMD) assessment.

Methods: The PubMed, EBSCO, Ovid, Web of Science, Cochrane Library, Wanfang, China National Knowledge Infrastructure, Chinese Science and Technology Periodical databases were searched to retrieve original studies on VBQ and BMD published from inception to 31 December 2023 with no restrictions on language and the reference standard of BMD. The quality of the included articles was assessed using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2). Summary accuracy metrics were obtained by bivariate random-effects meta-analysis. The area under the curve (AUC) of the summary receiver operating characteristic (SROC) analysis was used to evaluate the performance of the VBQ score. Meta-regression and subgroup analyses were performed to examine the source of heterogeneity.

Results: In total, 23 studies, comprising 2981 patients, from 2022 to 2023, of high- or medium-to-high scientific quality were included in the meta-analysis. The pooled sensitivity, specificity, and diagnostic odds ratio (DOR) of the VBQ score in the assessment of BMD were 0.77 [95% confidence interval (CI), 0.73–0.81; $P < 0.001$], 0.65 (95% CI, 0.59–0.71; $P < 0.001$), and 6.49 (95% CI, 4.82–8.73; $P < 0.001$), respectively, with an area under the SROC curve of 0.78 (95% CI, 0.74–0.82; $P < 0.001$). The presence of heterogeneity was found to have a significant association with factors such as the reference standard, sex, mean age, region of publication, VBQ method, and magnet field strength.

Conclusions: The MRI-based VBQ score has some diagnostic value in detecting osteoporosis. The VBQ score could be used as a tool for opportunistic osteoporosis screening before spine surgery.

Keywords: Osteoporosis; bone mineral density (BMD); vertebral bone quality (VBQ); diagnostic value; meta-analysis

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Introduction

Osteoporosis is the most common skeletal disorder worldwide, and is becoming more common among postmenopausal women, and the general population aged over 50 years. The prevalence of osteoporosis and its related fractures is increasing as life expectancy increases (1). Osteoporosis is characterized by microarchitecture deterioration in bone tissue and decreased bone mass (1), and it increases bone fragility and susceptibility to fracture. A systematic review reported that the global prevalence of osteoporosis among individuals aged 15–105 years was 18.3% (2), and nearly 9 million osteoporotic fractures occur annually (3). Osteoporosis and the resultant fragility fractures contribute to increased morbidity and mortality, the need for long-term care facilities, and economic costs (4). Thus, the early diagnosis and treatment of osteoporosis is critical.

Dual-energy X-ray absorptiometry (DXA) is currently the reference standard for diagnosing bone mineral density (BMD) (5). It has become one of the most widely used techniques for the assessment of BMD, as it is inexpensive, easy to use, and has a low radiation dose. However, DXA also has some drawbacks in terms of its utility, as it tends to overestimate BMD in patients with aortic calcifications, degenerative spines, or a high body mass index (BMI) (5–7), all of which are common in the elderly and those seeking spine surgery treatment. DXA assessment can also be inaccurate in patients with scoliosis (8). In addition, DXA cannot distinguish between cortical and trabecular bone. Thus, it cannot provide detailed information about skeletal strength and bone microarchitecture. Quantitative computed tomography (QCT) provides accurate volumetric BMD (vBMD) measurements, and can overcome the deficiencies of DXA, but its radiation is higher than that of DXA. These limitations have prompted research into other techniques to diagnose osteoporosis.

Several previous studies have sought to establish a magnetic resonance imaging (MRI)-based method for quantifying BMD to decrease patient radiation exposure and overall care expenses (9,10). These studies have found that as bone becomes osteoporotic, the trabecular portion becomes more hyperintense on T1-weighted imaging (T1WI), and that bone marrow signal intensity (SI) is negatively correlated with BMD. This may be due to the high signal shown when fat infiltrates bone, as previous

studies have shown that osteoporotic bone is characterized by trabecular atrophy and local adipocyte replacement (11). Further, research has shown that vertebral SI on lumbar spine MRI-T1WI can more sensitively evaluate BMD than DXA (12).

Ehresman *et al.* first proposed the MRI-based vertebral bone quality (VBQ) score as a novel method for evaluating BMD (13). The VBQ score is calculated based on non-contrast T1-weighted MRI in the midsagittal plane. First, a region of interest (ROI) is manually placed in the medullary bone of the L1–L4 vertebral bodies, and in the cerebrospinal fluid (CSF) space at the level of L3, and the average SIs in each ROI are recorded. The VBQ score is calculated by dividing the median SI of the vertebral bone by the mean SI of the CSF results. Ehresman *et al.* found that the VBQ score could be used to differentiate between healthy and osteopenic/osteoporotic bone, and was moderately correlated with the femoral neck and overall lowest T-scores (13). MRI is a routine preoperative examination tool that is readily available and ionizing radiation free. Thus, the VBQ score could serve as an opportunistic osteoporosis screening tool for patients undergoing spine surgery. It enables surgeons to evaluate nerve and spinal cord conditions, while providing a more widely available of clinically opportunistic screening for BMD to patients in an economic-efficient and radiation-free manner, thereby reducing unnecessary radiation exposure.

The use of the VBQ score to evaluate osteoporosis has been the subject of many recently published studies. However, there is a lack of consensus on the diagnostic value of the VBQ score in assessing BMD, and varying thresholds have been used throughout the literature. Chen *et al.* conducted the first meta-analysis to examine the diagnostic value of VBQ (14). However, due to the high heterogeneity and limited sample size of the studies included in the meta-analysis, Chen *et al.* did not conduct any further analyses to investigate the source of heterogeneity, which might have led to results bias. Therefore, we performed this systematic review and meta-analysis to explore the value of the MRI-based VBQ score in evaluating abnormal BMD and the source of heterogeneity. Our findings provide a comprehensive overview of the effectiveness of the MRI-based VBQ score in identifying BMD. We present this article in accordance with the PRISMA-DTA reporting checklist (15) (available at <https://qims.amegroups.com/article/view/10.21037/qims-24-532/rc>).

Methods

Data sources and search strategy

A systematic search of the following electronic databases was performed to retrieve articles published from the inception of the databases to December 31, 2023: PubMed, EBSCO, Ovid, Web of Science, and Cochrane Library. We also searched Chinese electronic databases, including the Wanfang, China National Knowledge Infrastructure (CNKI), Chinese Science and Technology Periodical (VIP) databases. The reference lists of the articles were reviewed to identify any additional relevant studies that were not found in the primary searches. The following keywords were used in the search: (osteoporosis OR bone loss OR osteopenia OR BMD OR bone mineral density) AND (magnetic resonance imaging OR MRI OR MR) AND (VBQ OR vertebral bone quality). The search strategy is shown in [Table S1](#). Our search was registered in the PROSPERO database with all the necessary details (No. CRD42024501549).

Study selection

To be eligible for inclusion in this meta-analysis, the studies had to meet the following inclusion criteria: (I) population: include patients aged >18 years; (II) index test: include patients who had undergone MRI and DXA/QCT for whom MRI-VBQ scores had been used as the diagnostic tool for BMD; (III) outcomes: focus on diagnosing BMD and include sufficient data to reconstruct 2×2 tables to determine sensitivity and specificity; (IV) have been published as original articles. Studies were excluded from the meta-analysis if they met any of the following exclusion criteria: (I) had a sample size <10 patients; (II) had a manuscript type that comprised a case report, animal trial, review article, systematic review, meta-analysis, commentaries, editorial, or meeting abstract; and/or (III) had an overlapping patient population. If there was a similarity between the study populations, the study with the largest and most recent sample was chosen. When 2×2 tables could not be established, the authors of the eligible studies were contacted for more information.

Data extraction

Two reviewers (D.Y. and C.L., with 5 years and 8 years of experience in radiology, respectively) independently reviewed the included studies to extract and enter the key

data elements into pre-designed data abstraction forms. Any discrepancies were resolved by consensus review. The extracted data included the first author, publication year, publication region, study design, duration of patient recruitment, participant characteristics, sample size, identification of bone status, reference standard, magnet field strength, VBQ method, sensitivity, specificity, numbers of true/false positives and true/false negatives, area under the curve (AUC), and VBQ score threshold.

Quality assessment

The articles included in this study were assessed for bias and clinical applicability using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) tool (16).

Data synthesis and statistical analysis

The statistical analysis was performed using MetaDiSc 1.4 software (Universidad Autónoma de Madrid, Spain), RevMan software (version 5.3.2; Cochrane Collaboration), and STATA (version 14.0, STATA Corp., Texas, USA) with the MIDAS module. The presence of heterogeneity due to threshold effects was tested using the Spearman correlation coefficient between the log of sensitivity and the log of 1-specificity. A Spearman correlation coefficient >0.6 indicated a threshold effect (17). Diagnostic accuracy data (true/false positive and true/false negative) extracted from the included studies were used to calculate the sensitivity, specificity, positive likelihood ratio (PLR), negative likelihood ratio (NLR), and diagnostic odds ratio (DOR) for all individual studies and their corresponding pooled measurements at 95% confidence intervals (CIs). Pooled estimates along with 95% CIs and the AUCs of the summary receiver operating characteristic (SROC) curves were calculated. The closer the AUC was to 1, the higher the diagnostic efficacy of a test or model. Publication bias was investigated using Deeks' funnel plot asymmetry test. A P value <0.05 indicated significant publication bias. Heterogeneity due to non-threshold effects was assessed using the Cochran-Q test and Higgins inconsistency index (I^2) test. Heterogeneity was considered moderate when I^2 exceeded 50% and high when I^2 exceeded 75% (18). If significant heterogeneity was detected, meta-regression and subgroup analyses were conducted to explore the source of the heterogeneity. This study pre-specified five covariates (i.e., the reference standard, sex, mean age, region of publication and VBQ method), and pre-specified

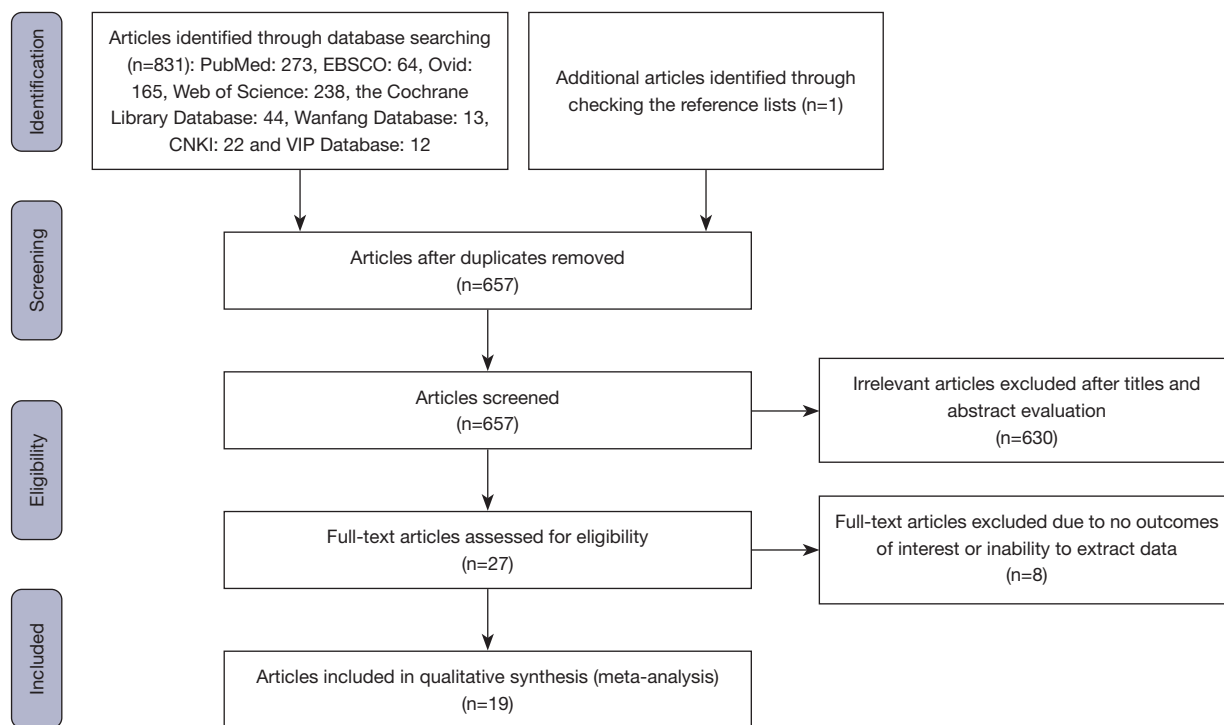


Figure 1 Literature selection process.

three subgroups based on the magnet field strength, VBQ measurement region, and identification of bone status, respectively. A sensitivity analysis was performed to assess whether the results of the meta-analysis were stable.

Results

Literature search

The detailed literature selection process is shown in *Figure 1*. Initially, 831 articles were retrieved from the systematic literature search of the relevant databases, and one additional article was identified by checking the reference lists of the retrieved articles. Thus, in total, 832 articles were initially identified. After removing the duplicate articles, the titles and abstracts of the remaining 657 articles were screened, yielding 27 potentially eligible articles. The full text of the remaining articles was then reviewed, and eight additional articles were excluded because they either did not report results of interest (i.e., include diagnostic data on the VBQ evaluation of BMD), or 2×2 columnar data could not be extracted. Ultimately, 19 articles (19-37), comprising 23 studies (one article contained three studies, and two articles contained two studies each), were included

in this meta-analysis.

Assessment of study quality

Figure 2 provides graphical representations of the QUADAS-2 risk assessment results. In terms of the risk of bias evaluation, the “patient selection” domain was rated low risk for all studies, as all the patients were enrolled consecutively, case-control designs were avoided, and there were no inappropriate exclusions of cases. The “index test” domain was rated high risk for all studies, as 13 studies were unclear as to whether the MRI analysis had been performed by a clinician blinded to the reference standard (19-21,24,27,29,34-37), and none of the included studies had a predefined threshold of the MRI-based VBQ score. The “reference standard” domain was rated low risk for all studies, as the reference standard (DXA or QCT) was able to correctly classify the patient’s BMD condition (normal or osteopenia/osteoporosis), and the individual interpreting the results of the reference standard (DXA or QCT) was fully blinded to the MRI. In relation to the “flow and timing” domain, one study (20) was rated high risk, as there was not an appropriate interval between MRI and DXA (the patients received the DXA scan 3 years before or after the

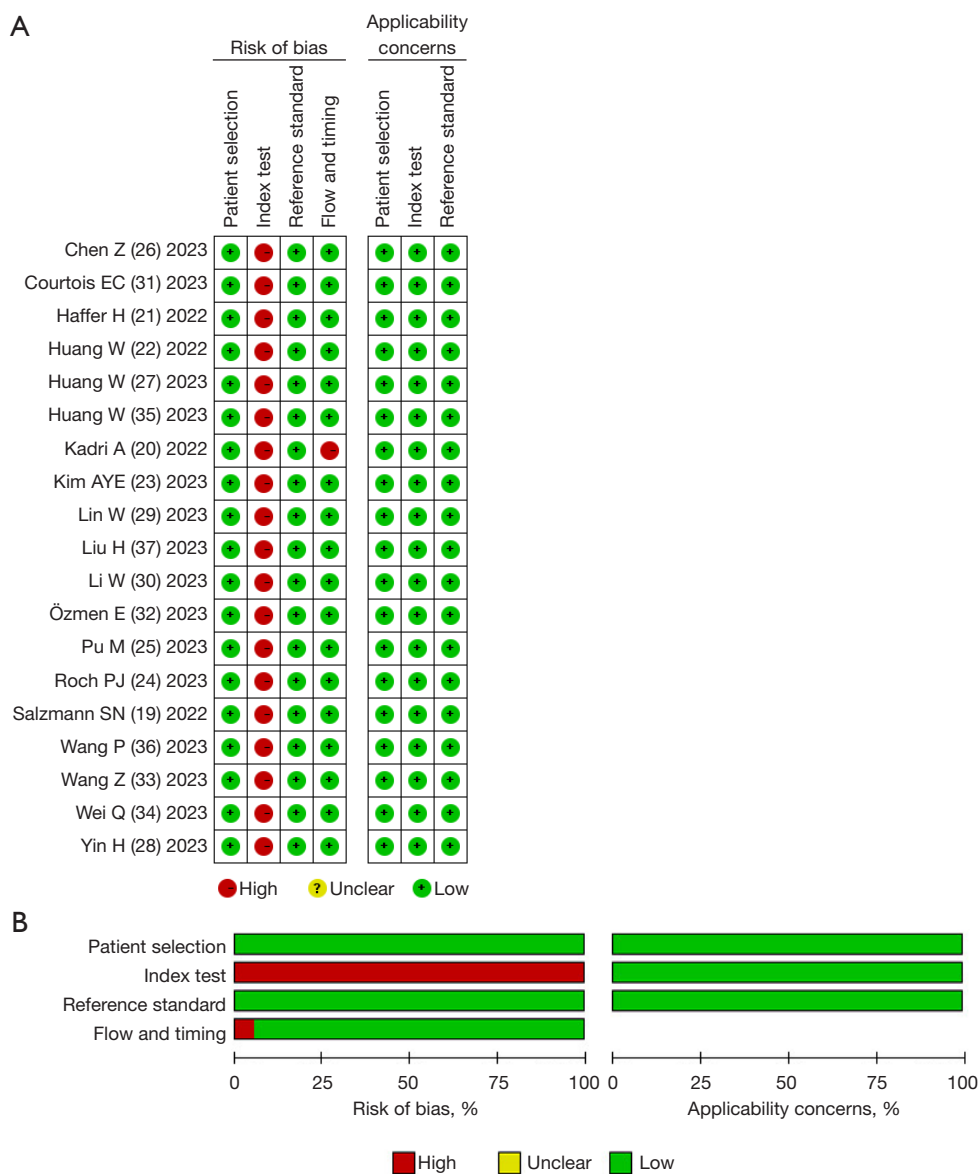


Figure 2 Quality assessment of the diagnostic accuracy of the included studies. (A) Risk of bias and applicability concerns graph: review authors’ judgements about each domain; presented as percentages among included studies. (B) Risk of bias and applicability concerns summary: review authors’ judgements about each domain for each included study.

MRI), and the remaining 22 studies were rated low risk, as there was an appropriate time interval between the included studies (no more than 1 year between the DXA/QCT and MRI scans), the same and only reference standard (DXA or QCT) was used for all the patients, and all the patients were included in the analysis. In relation to the evaluation of the applicability concerns, the risks for “patient selection”, the “index test”, and the “reference standard” were rated low for all studies, as the included patients matched the evaluation

value of the MRI-based VBQ scores for evaluating BMD, the VBQ scores were applicable to the evaluation of BMD, and DXA and QCT were applicable to the evaluation of BMD.

Study and patient characteristics

Tables 1,2 provide details of the study and patient characteristics. Of the 23 studies, 15 were performed in

Table 1 Characteristics of the articles included in the present meta-analysis

ID	First author	Year	Region	Design	Duration	Age (year), mean (SD)	Female, n (%)	BMI (kg/m ²), mean (SD)	Sample size		Identification of bone quality status	Reference standard (DXA T-score/QCT)	Field strength (T)
									Osteopenia/osteoporosis (n)	Normal BMD (n)			
1	Salzmann SN (19)	2022	USA	R	2014–2019	62.00 (NR)	104 (52.50)	28.20 (SD)	128	70	Normal vs. osteopenia/osteoporosis	QCT	NR
2	Kadri A (20)	2022	USA	R	2017.9–2020.9	70.10 (8.36)	66 (79.50)	28.93 (5.96)	35/31	17	Normal vs. osteopenia/osteoporosis	DXA	1.5 or 3.0
3	Huang W (22)	2022	China	R	2020.9–2022.3	66.10 (7.20); 66.70 (7.10)	46 (55.50)	24.30 (2.40); 23.60 (3.00)	63	20	Normal vs. osteopenia/osteoporosis	DXA	1.5 or 3.0
4	Haffer H (21)	2022	USA	R	2014–2021	63.30 (12.20)	149 (55.80)	29.70 (6.20)	174	93	Normal vs. osteopenia/osteoporosis	QCT	NR
5	Roch PJ (24)	2023	Germany	R	2017–2021	69.70 (15.00)	77 (56.60)	27.00 (5.00)	108	28	Normal vs. osteopenia/osteoporosis	QCT	NR
6	Chen Z (26)	2023	China	R	2019.7–2020.6	59.40 (7.80)	97 (72.40)	23.90 (3.10)	107	27	Normal vs. osteopenia/osteoporosis	DXA	NR
7	Li W (30)	2023	China	R	2019.1–2021.7	59.4 0 (9.60)	80 (61.50)	25.69 (3.24)	51/59	20	Non-osteoporosis vs. osteoporosis	DXA	NR
8	Lin W (29)	2023	China	R	2020.9–2022.11	68.90 (9.90)	354 (78.30)	23.80 (3.70)	58/109	12	Non-osteoporosis vs. osteoporosis	QCT	3.0
9	Wang Z (33)	2023	China	R	2015.1–2022.12	51.95 (10.94)	58 (54.70)	24.67 (4.20); 24.33 (3.95)	72	34	Normal vs. osteopenia/osteoporosis	DXA	NR
10	Courtois EC (31)	2023	USA	R	2018–2022	46.10 (NR)	169 (39.70)	28.40 (11.30); 26.80 (4.00); 27.60 (1.88)	4/67	355	Normal vs. osteopenia/osteoporosis	DXA	NR
11	Kim AYE (23)	2023	USA	R	2016.1–2021.5	64.00 (12.00)	37 (60.70)	28.10 (5.90)	21/19	21	Non-osteoporosis vs. osteoporosis	QCT	NR
12	Yin H (28)	2023	China	R	2020.9–2022.10	68.70 (10.10)	208 (80.00)	23.80 (3.75)	NR/165	NR	Non-osteoporosis ^a vs. osteoporosis	QCT	1.5
13	Pu M (25)	2023	China	R	2018.9–2021.9	66.10 (9.40)	100 (100.00)	25.80 (4.40); 25.00 (3.70); 23.40 (3.60)	45/32	23	Normal vs. osteoporosis	DXA	1.5
14	Özmen E (32)	2023	Turkey	R	NR	63.39 (11.11)	111 (85.40)	30.99 (5.25)	63/24	43	Non-osteoporosis vs. osteoporosis	DXA	NR
15	Huang W (27)	2023	China	R	2019.1–2022.6	66.9 0 (8.00); 68.1 0 (7.10); 71.0 0 (5.60)	149 (72.00)	26.00 (3.40); 24.80 (3.00); 23.40 (3.40)	103/64	40	Normal vs. osteopenia/osteoporosis	DXA	NR
16	Liu H (37)	2023	China	R	2017.1–2021.5	66.88 (6.33); 68.57 (6.29)	163 (100.00)	25.48 (3.55); 24.84 (3.89)	115	48	Normal vs. osteopenia/osteoporosis	DXA	1.5
17	Wei Q (34)	2023	China	R	2018.1–2022.8	63. 91 (7.41)	210 (100.00)	NR	166	44	Normal vs. osteopenia/osteoporosis	DXA	1.5
18	Huang W (35)	2023	China	R	2020.9–2022.3	67.00 (7.10)	37 (52.10)	24.22 (2.30); 23.51 (3.12)	54	17	Normal vs. osteopenia/osteoporosis	DXA	NR
19	Wang P (36)	2023	China	R	2019.1–2020.8	63.10 (9.80); 70.10 (7.70)	57 (69.50)	31.50 (5.40); 28.40 (4.90)	42	40	Normal vs. osteopenia/osteoporosis	DXA	1.5

^a, the number of non-osteoporosis = 95 (osteopenia + normal). SD, standard deviation; BMI, body mass index; BMD, bone mineral density; DXA, dual-energy X-ray absorptiometry; QCT, quantitative computed tomography; R, retrospective; NR, not reported.

Table 2 Methodology assessment of the studies included in the present meta-analysis

ID	First author	VBQ method	TP	FP	FN	TN	AUC	Threshold	Sen	Spe
1	Salzmann SN (19)	Median L1–L4/L3 CSF	95	30	33	40	0.70	2.38	0.74	0.57
2	Kadri A/a (20)	Median L1–L4/L3 CSF	51	4	15	13	0.82	3.12	0.78	0.75
3	Kadri A/b (20)	L1 /L1 CSF	58	5	8	12	0.82	3.01	0.88	0.69
4	Huang W (22)	Mean C2–C7/T1 CSF	58	8	5	12	0.78	2.90	0.92	0.60
5	Haffer H (21)	Median L1–L4/L3 CSF	147	55	27	38	0.67	2.18	0.84	0.40
6	Roch PJ (24)	Mean L1–L4/L3 CSF	69	6	39	22	0.71	2.10	0.64	0.78
7	Chen Z (26)	Median L1–L4/L3 CSF	94	14	13	13	NR	NR	0.87	0.48
8	Li W/a (30)	L1 /L1 CSF	45	25	14	46	0.70	3.26	0.76	0.64
9	Li W/b (30)	Median L1–L4/L3 CSF	41	26	18	45	0.67	3.20	0.69	0.63
10	Lin W (29)	Mean L1–L4/mean CSF (L1–L3)	73	21	36	49	0.70	2.59	0.67	0.69
11	Wang Z/a (33)	Mean C2–C7/T2 CSF	50	10	22	24	0.72	2.99	0.69	0.70
12	Wang Z/b (33)	Median C3–C6/C2 CSF	51	11	21	23	0.71	3.17	0.70	0.67
13	Wang Z/c (33)	Median C3–C6/C5 CSF	45	8	27	26	0.71	3.00	0.62	0.76
14	Courtois EC (31)	Median L1–L4/L3 CSF	39	173	32	182	0.55	2.50	0.54	0.51
15	Kim AYE (23)	Median L1–L4/L3 CSF	11	4	8	38	0.75	2.60	0.58	0.90
16	Yin H (28)	Median L1–L4/mean CSF (L1–L3)	134	42	31	53	0.73	3.70	0.81	0.55
17	Pu M (25)	Median L1–L4/L3 CSF	28	9	4	14	0.81	3.05	0.87	0.61
18	Özmen E (32)	Mean L1–L4/L3 CSF	20	59	4	47	0.66	2.70	0.83	0.44
19	Huang W (27)	S1 VBQ = S1/CSF L3	129	12	38	28	0.82	2.93	0.77	0.70
20	Liu H (37)	Mean L1–L4/L3 CSF	99	12	16	36	0.81	3.08	0.86	0.75
21	Wei Q (34)	Mean L1–L4/L3 CSF	135	16	31	28	0.77	3.24	0.81	0.64
22	Huang W (35)	Mean C2–C7/T1 CSF	44	5	10	12	0.81	3.19	0.81	0.70
23	Wang P (36)	Mean L1–L4/L3 CSF	34	5	8	35	0.93	2.98	0.81	0.88

VBQ, vertebral bone quality; TP, true positive; FP, false positive; FN, false negative; TN, true negative; AUC, area under the curve; Sen, sensitivity; Spe, specificity; CSF, cerebrospinal fluid; NR, not report.

China, six in the United States of America, one in Germany, and one in Turkey. The study sample size comprised 2,981 patients (range, 55–426 per study), and the patients were all enrolled consecutively. All the included studies were retrospective (cross-sectional) studies. The average age of the patients ranged from 46 to 71 years, and the average BMI ranged from 23.40 to 31.50 kg/m². Females accounted for 76.21% of the patient cohort. Of the 23 studies, 17 used the DXA T-score as the reference standard for assessing BMD, and 1,291 patients were diagnosed with osteopenia/osteoporosis, and 773 patients were identified as having normal BMD. The remaining six studies used QCT as the reference standard, and 643 patients were diagnosed with

osteopenia/osteoporosis and 274 with normal BMD.

Diagnostic accuracy

The Spearman correlation coefficient between the log of sensitivity and the log of 1–specificity was 0.36 (P=0.09), which was not significant; thus, no threshold effect was found in this study. The symmetric SROC curve was plotted, and no “shoulder-arm shape” was found, which provided further evidence that there was no threshold effect. The Cochran-Q test for the DOR showed that heterogeneity due to non-threshold effects was present (Q=63.66, P<0.01). Further, as the I² of the sensitivity,

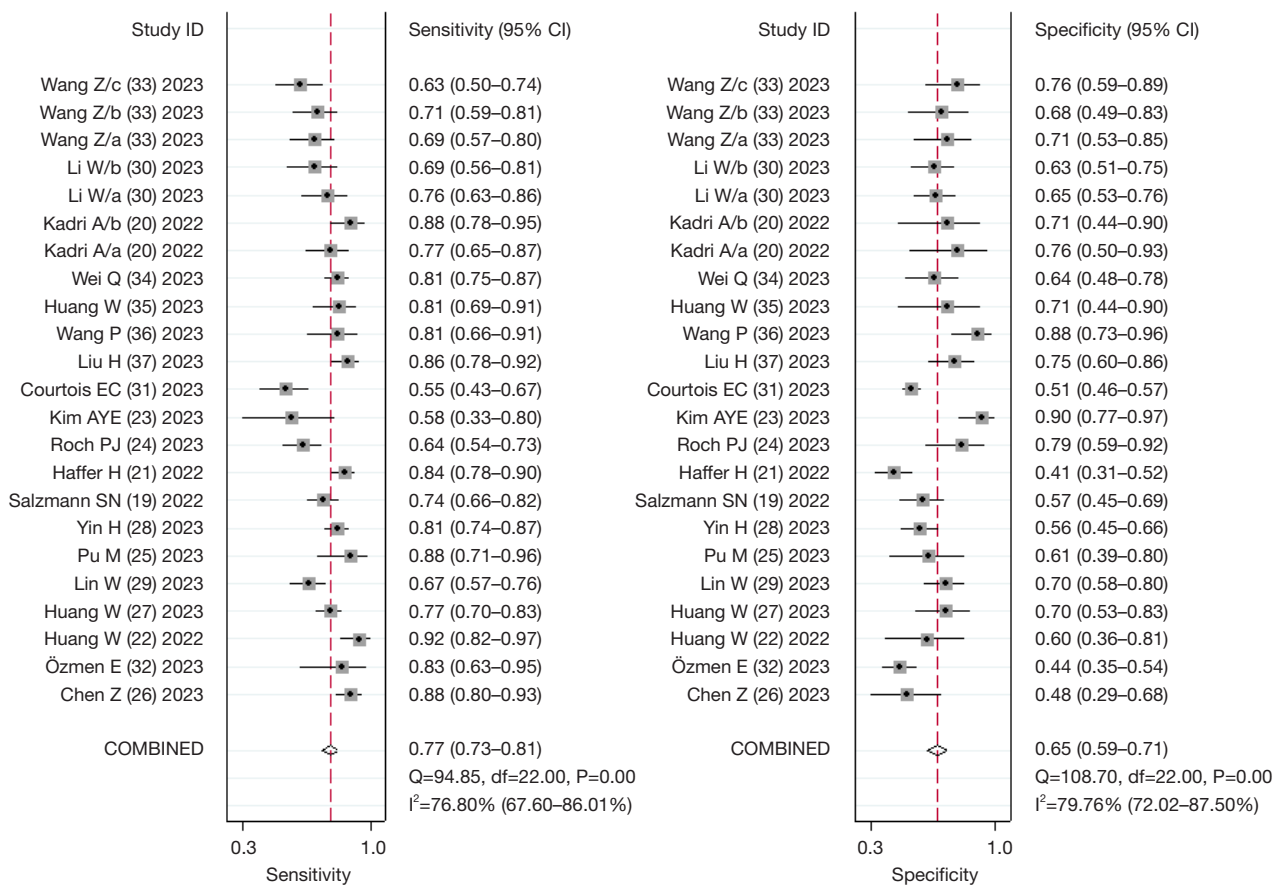


Figure 3 Forest plots of the sensitivity (left) and specificity (right) of the MRI-VBQ score for assessing BMD. Each solid square represents an individual study. Error bars represent 95% CIs. CI, confidence interval; MRI, magnetic resonance imaging; VBQ, bone quality score; BMD, bone mineral density.

specificity, PLR, NLR, and DOR in this study were all >50%, the random-effects model was used to combine the evaluation indicators.

The pooled sensitivity was 0.77 (95% CI, 0.73–0.81; $I^2=76.80\%$, $P<0.001$), the pooled specificity was 0.65 (95% CI, 0.59–0.71; $I^2=79.76\%$, $P<0.001$), the pooled PLR was 2.24 (95% CI, 1.90–2.64; $I^2=63.40\%$, $P<0.001$), the pooled NLR was 0.35 (95% CI, 0.29–0.41; $I^2=73.46\%$, $P<0.001$), the pooled AUC was 0.78 (95% CI, 0.74–0.82; $P<0.001$), and the DOR was 6.49 (95% CI, 4.82–8.73; $I^2=100\%$, $P<0.001$) (Figures 3–6).

Meta-regression

The I^2 test revealed obvious heterogeneity among the studies. To analyze the source of the heterogeneity, five covariates (i.e., the reference standard, sex, mean age,

region of publication, and VBQ method), were included in the meta-regression analysis to assess their effect on heterogeneity. The results showed that sensitivity was influenced by the reference standard, sex, mean age, region of publication, and VBQ method, while specificity was affected by the VBQ method (Figure 7).

Subgroup analysis

A subgroup analysis based on the magnet field strength was conducted to evaluate the diagnostic performance of the VBQ score for detecting BMD (Figure S1). The pooled sensitivity of the subgroup analysis of five studies that used 1.5-T MRI (25,28,34,36,37) was 0.83 (95% CI, 0.79–0.86; $I^2=0.00$), and the pooled specificity was 0.69 (95% CI, 0.57–0.79; $I^2=73.82\%$). An additional subgroup analysis was conducted of 17 studies (19–24,26,27,30–33,35),

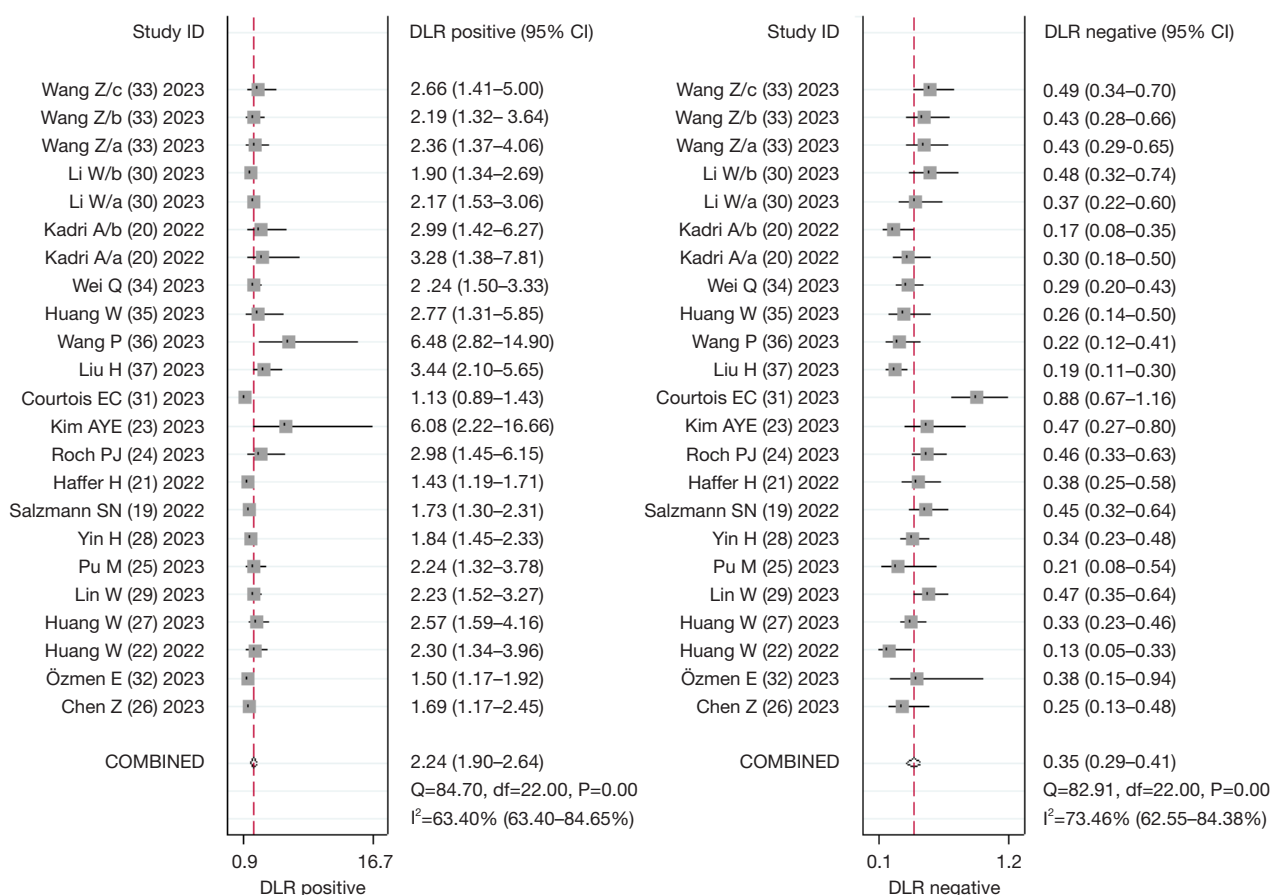


Figure 4 Forest plots of the positive likelihood ratio (left) and negative likelihood ratio (right) of the MRI-VBQ score for assessing BMD. Each solid square represents an individual study. Error bars represent 95% CIs. DLR, diagnostic likelihood ratio; CI, confidence interval; MRI, magnetic resonance imaging; VBQ, bone quality score; BMD, bone mineral density.

but the results about magnet field strength were not clear. The pooled sensitivity of this subgroup was 0.76 (95% CI, 0.71–0.81; $I^2=78.00\%$), and the pooled specificity was 0.64 (95% CI, 0.56–0.71; $I^2=80.44\%$). The sensitivity of the only study (29) that used 3.0-T MRI was 0.67 (95% CI, 0.57–0.76), and the specificity was 0.70 (95% CI, 0.58–0.80).

In the subgroup analysis of cervical VBQ (22,33,35) and lumbar VBQ (19-21,23-26,28-32,34,36,37), the pooled sensitivity was 0.76 (95% CI, 0.65–0.85; $I^2=78.74\%$) and 0.78 (95% CI, 0.73–0.82; $I^2=78.61\%$), and the pooled specificity was 0.69 (95% CI, 0.60–0.77; $I^2=0.00$) and 0.65 (95% CI, 0.57–0.72; $I^2=83.54\%$), respectively (Figure S2).

In the distinguishing normal from osteopenia/osteoporosis subgroup analysis (19-22,24-27,31,33-37), the pooled sensitivity was 0.79 (95% CI, 0.74–0.83; $I^2=80.63\%$), and the pooled specificity was 0.66 (95% CI, 0.59–0.72;

$I^2=79.25\%$). In the distinguishing osteoporosis from non-osteoporosis subgroup analysis (29,30,23,28,32), the pooled sensitivity was 0.73 (95% CI, 0.64–0.81; $I^2=57.44\%$), and the pooled specificity was 0.66 (95% CI, 0.53–0.76; $I^2=84.58\%$) (Figure S3).

Sensitivity analysis

After removing the studies one by one, no significant effect was found, suggesting that our findings were stable and plausible (Figure 8).

Publication bias analysis

The Deeks’ funnel plot test revealed a $P<0.01$, which suggested that there was publication bias (Figure 9).

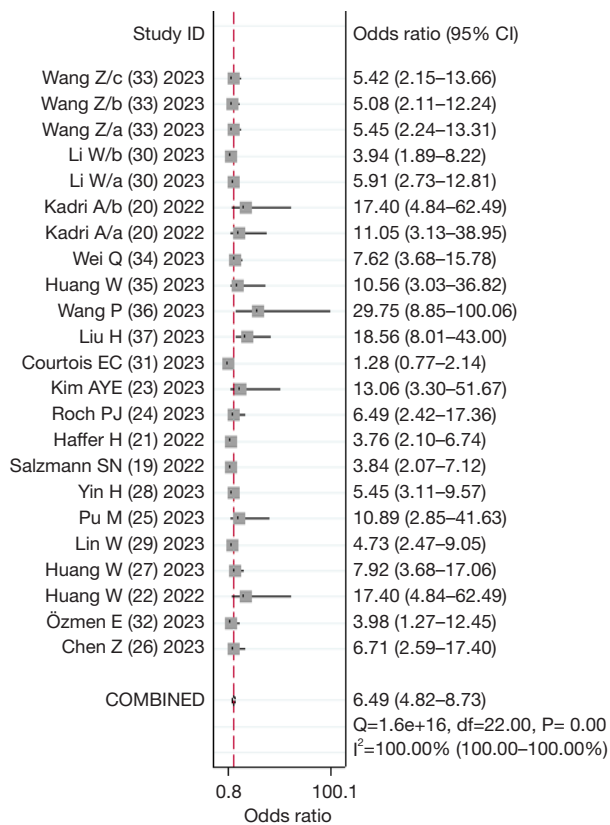


Figure 5 Forest plots of the diagnostic odds ratio of the MRI-VBQ score for assessing BMD. Each solid square represents an individual study. Error bars represent 95% CIs. CI, confidence interval; MRI, magnetic resonance imaging; VBQ, bone quality score; BMD, bone mineral density.

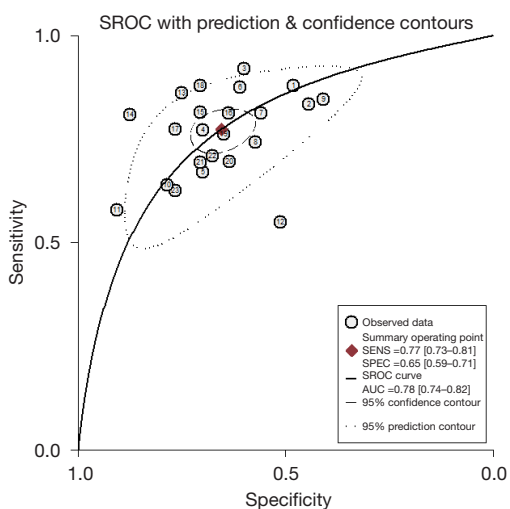


Figure 6 SROC analysis. SROC, summary receiver operating characteristic curve; AUC, area under the curve.

Discussion

MRI is frequently used in the preoperative assessment of spine surgery patients, and recently, its use as a possible alternative to the BMD evaluation has been investigated. Studies have shown that the occurrence of osteoporosis is often characterized by trabecular atrophy and an increase in bone marrow adipocytes (11). Many quantitative methods have been used to measure the bone trabecular microstructure or bone marrow fat content based on differences in SIs within bone tissues (9,10,13,38-40). Changes in these parameters have been found to be negatively correlated with osteoporosis and bone quality. Bandirali *et al.* (9) first introduced the “M-score” in 2015 as a new MRI-based score simulating DEXA T-score calculation, and reported that it had a diagnostic precision of 84.4% in differentiating between osteoporosis and non-osteoporosis. It was further evaluated by other studies, and these studies reported that it had a better correlation with BMD than other MRI measures (pooled $r^2=-0.58$). However, the clinical utility of the M-score is limited because it relies on signal-to-noise ratios that are specific to the MR system in use, and M-score values vary between devices. In 2019, Ehresman *et al.* proposed a novel, scanner-independent, T1-weighted MRI-based score for evaluating patient BMD; that is, the VBQ score (13). The VBQ score was calculated using MR volumes acquired by four distinct MR systems, and no significant difference in the VBQ scores was found between the machines tested. Thus, the VBQ score may have greater generalizability and clinical utility than the M-score.

Considerable research has been conducted since Ehresman *et al.* first described the use of the VBQ score as a diagnostic tool for osteoporosis. The specific VBQ method employed has varied across studies, with some using median or mean measurements at different spinal levels (e.g., L1–L4, L3, C2–C7) and dividing them by CSF for standardization. The studies have reported a range of AUCs (0.55–0.93), sensitivity values (0.54–0.92), and specificity values (0.40–0.90), which shows that the accuracy of the VBQ in assessing BMD varies. We found that the VBQ score had a high accuracy of 0.78 for the diagnosis of bone loss with a pooled sensitivity of 0.77 and a pooled specificity of 0.65. Thus, the VBQ score can be used as a simple, effective tool for differentiating between normal BMD and bone loss. Additionally, the pooled DOR showed that the probability of correctly diagnosing an individual with bone loss was 6.49 times higher than a false-negative diagnosis in

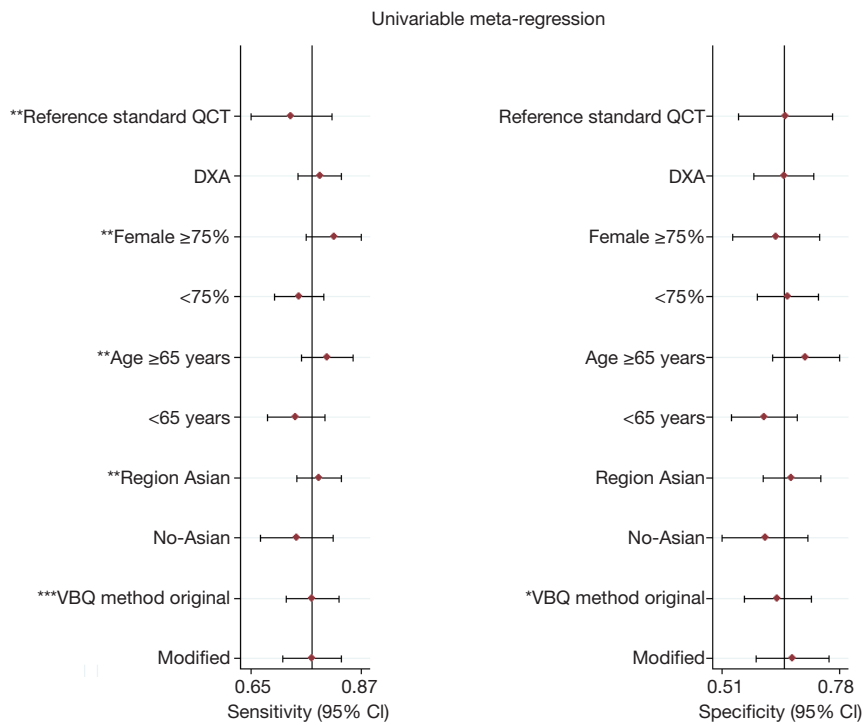


Figure 7 Univariate meta-regression for sensitivity and specificity of the VBQ score for the diagnosis of bone density. *, P<0.05; **, P<0.01; ***, P<0.001. QCT, quantitative computed tomography; DXA, dual-energy X-ray absorptiometry; VBQ, bone quality score; CI, confidence interval.

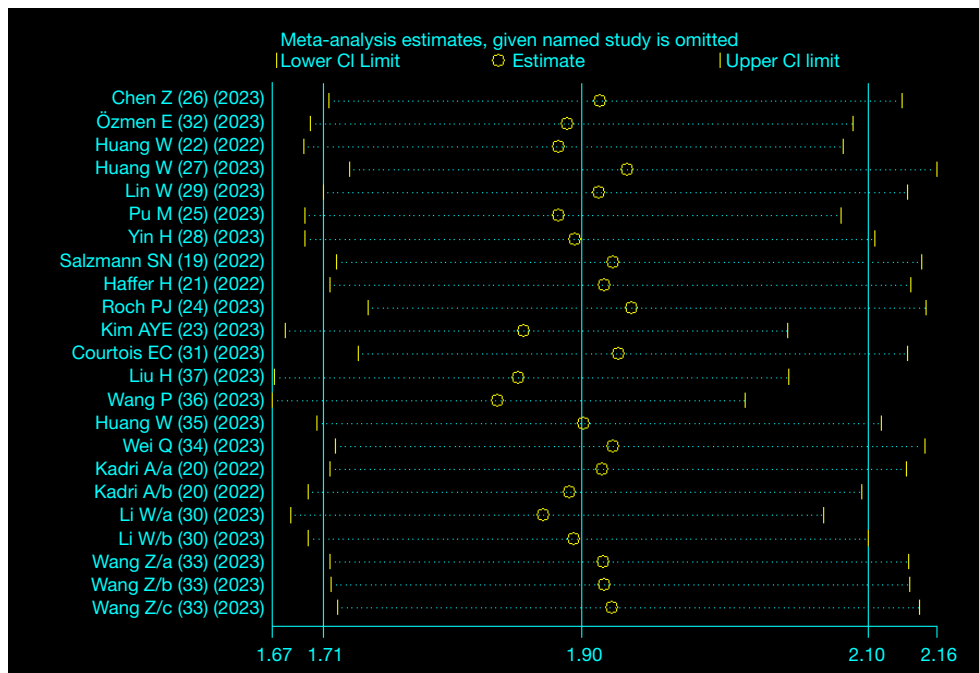


Figure 8 Sensitivity analysis of the study. CI, confidence interval.

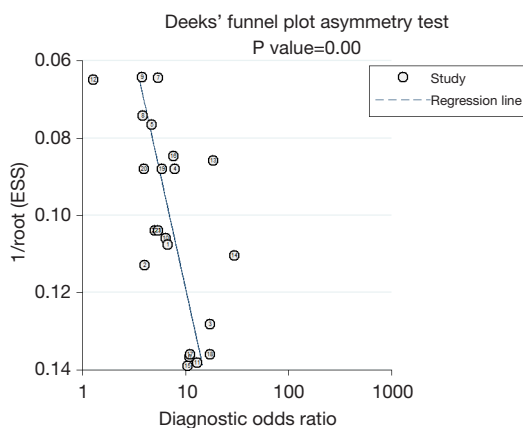


Figure 9 Funnel plot for the assessment of publication bias. ESS, effective sample size.

a healthy individual.

Heterogeneity was found in this meta-analysis. Specifically, we found that the reference standard, sex, mean age, region of publication, VBQ method, and magnetic field strength were potential sources of heterogeneity. The reference standard for the diagnosis of osteoporosis used in the included studies was either DXA or QCT. A study by Lin *et al.* (41) of 296 postmenopausal women found that the lumbar BMD measurements were not in complete accord between the QCT and DXA. In addition, another study (29) found that the VBQ score was more strongly correlated with QCT-vBMD than with DXA T-scores. VBQ score results may be influenced by knowledge of reference standard results. Bone loss is observed more often in women and the elderly. Research has reported that the prevalence of osteoporosis in women is 23.10% worldwide, but only 11.70% in men (2). This might explain why age and sex had a significant influence on heterogeneity. In certain characteristic study cohorts, the lack of patients with osteoporosis may adversely distort the diagnostic performance of the VBQ score. Its diagnostic performance may be better in patient populations in which a large proportion of the population suffers from bone loss (e.g., study groups comprising much older and more female participants). For instance, Courtois *et al.* (31) examined patients with symptomatic degenerative disc disease, with a mean age of 46.10 years (no patient was older than 66 years), and the proportion of female and patients with bone loss was 39.70% and 16.70%, respectively. Courtois *et al.* found that the diagnostic accuracy of the VBQ score for differentiating between osteoporosis/osteopenia and

normal BMD was 0.55, with a sensitivity of 0.54 and a specificity of 0.51. Pu *et al.* (25) conducted a study of female patients older than 50 years who underwent spinal surgery, and found that the diagnostic accuracy of the VBQ score was 0.81, with a sensitivity of 0.87 and a specificity of 0.61.

In our subgroup analysis of the VBQ measurement region, the heterogeneity of specificity within the cervical subgroup decreased significantly, but no obvious change in the lumbar subgroup was observed. The heterogeneity of sensitivity was not significantly decreased in either subgroup. Razzouk *et al.* evaluated the associations among cervical, thoracic, and lumbar VBQ scores, and found that the thoracic VBQ score provided surrogate values for the lumbar VBQ score while the cervical VBQ score was distinct from the lumbar VBQ score (42). Therefore, VBQ may vary across different regions of the spine. The diagnostic accuracy of the VBQ score measured in different regions of the spine on the assessment of BMD and the associations among them are still unclear. Further research should be conducted to investigate the optimized calculation of VBQ measures to improve clinical utility of VBQ score for diagnosing BMD.

In addition, the VBQ measurement is based on MRI T1WI, and our subgroup analysis indicated that the field strength contributed to the influence of the diagnostic value of the VBQ score, which is consistent with the findings of Lin *et al.* (29), who found that the 1.5-T-VBQ score was better able to differentiate between osteoporotic and non-osteoporotic patients than the 3.0-T-VBQ score (AUCs =0.74 and 0.70, respectively). Considering the non-negligible difference in diagnostic performance for osteoporosis between the 1.5-T-VBQ and 3.0-T-VBQ scores, it is crucial to pay attention to the magnetic field strength when assessing the VBQ score.

Further, in this meta-analysis, more than half of the subjects were from China, which was also one of the sources of heterogeneity. Some studies have indicated that when diagnosing osteoporosis in elderly East Asian populations, it is necessary to consider their ethnic-specific bone properties, and have proposed that the BMD threshold should be optimized to accommodate these features (43-45). The 12 studies conducted in China using existing BMD diagnostic criteria might have overestimated the diagnosis of osteoporosis, which might have affected the diagnostic performance of the VBQ score. Due to the differences in BMD between ethnicities, further research needs to be conducted to establish BMD normative benchmarks for different ethnicities, and to determine the degree to which

ethnicity should be incorporated in future VBQ assessments for BMD.

The sensitivity analysis showed that the results of our study were stable and reliable. The Deeks' funnel plot results indicated that there was a high likelihood of publication bias in this study, which might be related to the fact that this study contains only English- and Chinese-language articles. Second, the small sample sizes of the included studies might have also contributed to the publication bias to some extent. Third, some studies might not have reported negative results.

The present study had some limitations. First, while we established rigorous inclusion criteria, publication bias was detected. Second, the majority of the population included in the study was from China, which limits the broad applicability of the findings. Third, all the articles included were retrospective and cross-sectional studies, which might have led to bias. The inclusion of more prospective studies could have helped to determine causality without the need to work backwards to understand outcomes, or identify influencing factors. Finally, bone specimens for histologic analysis could not be obtained. Thus, future studies should be conducted that include histologic analyses to contribute to our understanding of the biological nature of the VBQ score.

Conclusions

This meta-analysis showed that the MRI-based VBQ score has some diagnostic value in the detection of osteoporosis. The VBQ score could serve as a clinically useful tool for opportunistic osteoporosis screening before spine surgery.

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Footnote

Reporting Checklist: The authors have completed the PRISMA-DTA reporting checklist. Available at <https://qims.amegroups.com/article/view/10.21037/qims-24-532/rc>

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at <https://qims.amegroups.com/article/view/10.21037/qims-24-532/coif>). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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