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MAGNETIC RESONANCE IMAGING–BASED BIOMARKERS FOR QUANTITATIVE ASSESSMENT OF VERTEBRAL BONE QUALITY IN OSTEOPOROSIS: A SYSTEMATIC REVIEW

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ABSTRACT

Purpose: To systematically review and synthesise MRI-based quantitative studies evaluating vertebral bone marrow parameters and their correlation with bone mineral density (BMD) in osteoporosis, and to assess the diagnostic and clinical utility of these MRI-derived biomarkers.

Materials and Methods: A structured literature review was performed, including 22 original MRI-based studies and additional relevant technical and review articles. Eligible studies assessed vertebral bone marrow using quantitative or semi-quantitative MRI techniques and correlated imaging findings with DXA- or QCT-derived BMD. MRI methods included proton MR spectroscopy, chemical shift–encoded techniques (Dixon, mDIXON-Quant, IDEAL-IQ), diffusion-weighted and intravoxel incoherent motion imaging, susceptibility-based parameters (R2*, T2*), and signal-intensity–based metrics such as the vertebral bone quality (VBQ) score. Study design, imaging protocols, reference standards, and correlation outcomes were qualitatively analysed following PRISMA recommendations.

Results: Across studies, vertebral marrow fat fraction consistently demonstrated a moderate-to-strong inverse correlation with BMD, irrespective of sex, age group, or reference standard. Diffusion, perfusion, and susceptibility-based parameters showed more variable associations but provided complementary information on bone microstructure. VBQ score showed moderate correlation with DXA and independent predictive value for fragility fractures. Methodological heterogeneity in MRI protocols and outcome reporting precluded quantitative meta-analysis.

Conclusion: MRI-derived vertebral bone marrow biomarkers, particularly fat fraction and VBQ score, provide radiation-free assessment of bone quality beyond BMD. Heterogeneous methods precluded meta-analysis, underscoring the need for standardised, prospective multicentre studies.

KEYWORDS: Osteoporosis; Magnetic resonance imaging; Bone mineral density; Bone marrow fat; Vertebral bone quality; IDEAL-IQ; Dixon technique

INTRODUCTION

Osteoporosis (OP) is a prevalent systemic skeletal condition marked by diminished bone strength and heightened vulnerability to fragility fractures constituting a significant public health challenge in ageing population. More than 200 million people, especially the elderly are affected worldwide (1). It is marked by lower bone density which makes bones more fragile and more likely to break especially vertebral compression fractures(VCFs) (7).

According to a previous study, the disability rate of OP will triple by 2050, placing a significant financial and social strain on families and society as a whole (1,2). Increased bone marrow adipocytes and poor bone production are linked to OP (4,5).

Bone strength reflects not only bone mineral density (BMD) but also bone quality, including microarchitecture, marrow composition, and vascularity (6).

The World Health Organization currently recommends dual energy absorptiometry (DEXA) as the gold standard for measuring bone mineral density (BMD) and diagnosing osteoporosis (1,3,11).

DEXA provides only areal BMD and does not fully account for bone quality or fracture risk. Degenerative changes, vascular calcifications, and vertebral deformities further limit the accuracy of DXA, particularly in spinal assessment. Final reading gets impacted due to these reasons (2,3,6).

Magnetic resonance imaging (MRI) has garnered heightened attention as a radiation-free modality proficient in examining vertebral bone marrow and the trabecular microenvironment. A biological connection between marrow adiposity and bone loss was established by early MRI and MR spectroscopy studies, which showed that osteoporosis is linked to increased vertebral marrow fat content and changed marrow composition(4,5).

Recent advancements in chemical shift–encoded MRI techniques, including Dixon and IDEAL-IQ, facilitated accurate determination of marrow fat fraction throughout the vertebral column in standard clinical environments (8,10,14,19,20).

Recent research has enhanced this approach by integrating diffusion, perfusion, and susceptibility data, along with simplified signal-intensity ratings, to offer supplementary insights into bone microstructure and fracture risk (9,22,25, 26,31).

MRI-based quantitative studies indicate that vertebral marrow characteristics are associated with bone mineral density (BMD) and may reveal facets of skeletal fragility not captured by densitometry alone (8,16,19,24). Nonetheless, the techniques, MRI parameters, and clinical endpoints described exhibit significant variability across research, and the relative clinical significance of these MRI-derived biomarkers has yet to be distinctly established.

This review aims to systematically summarize and critically evaluate MRI-based quantitative studies that correlate vertebral bone marrow parameters with bone mineral density (BMD) in osteoporosis. It will assess their methodological approaches, diagnostic efficacy, and clinical significance, while also highlighting current limitations and future directions for incorporating MRI into osteoporosis evaluation.

MATERIALS AND METHODS:

A systematic literature review was conducted in December 2025 in accordance with PRISMA 2020 guidelines. PubMed, Scopus, and Web of Science databases were searched for articles published within the previous ten years using combinations of the following keywords: osteoporosis, DXA, computed tomography, and magnetic resonance imaging.

Studies were included if they:

1.involved human subjects,

2.compared MRI-based quantitative or semi-quantitative techniques with DXA or quantitative computed tomography (QCT) as reference standards, and

3.reported diagnostic performance or correlation with BMD.

Exclusion criteria included review articles, guidelines, editorials, conference abstracts, non-English publications, duplicate cohorts, animal studies, technical validation studies without clinical correlation, and studies without osteoporosis-related outcomes.

A total of 41 records were identified through reference list screening. Fifteen studies were excluded following title and abstract screening. After full-text review, 22 studies met the inclusion criteria (Figure 1).

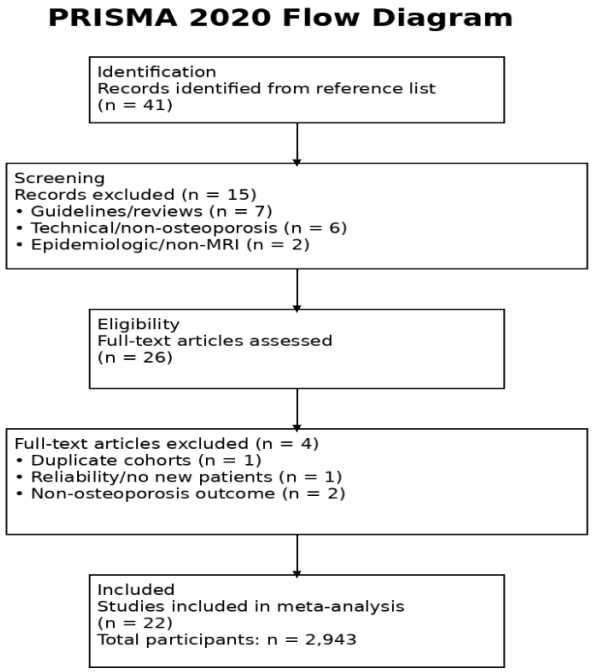

Figure 1: Flow Diagram of the studies selection process.

RESULTS:

Study Characteristics

The 22 included studies comprised predominantly prospective or retrospective observational diagnostic accuracy studies, along with technical validation and cohort analyses. Adult participants (≥18 years) who underwent spinal or hip MRI with contemporaneous DXA or QCT were included. Common exclusion criteria across studies included prior spinal surgery, vertebral fractures or focal lesions, metabolic or malignant bone disease, use of bone-active medications, and non-diagnostic MRI examinations.

A total of 2,943 participants were included in qualitative synthesis.

MRI Fat Fraction / PDFF–Based Studies (Table 1)

Eleven studies evaluated vertebral marrow fat fraction using MR spectroscopy, Dixon-based techniques, or IDEAL-IQ sequences (4,5,8,10,14,17,19,20,24,25, 28,30). Across studies, vertebral marrow fat fraction consistently demonstrated a moderate-to-strong inverse correlation with DXA- or QCT-derived BMD ($r \approx -0.4$ to -0.7). Fat fraction parameters effectively differentiated osteoporotic from non-osteoporotic individuals and were associated with vertebral fracture risk.

Diagnostic performance was favourable, with reported area under the curve (AUC) values ranging from 0.75 to 0.90. IDEAL-IQ and mDIXON techniques showed high reproducibility and feasibility for routine clinical use.

Table 1: MRI fat fraction PDFF based studies.

Study	Study design	year	N	Patient demographics	Inclusion/ exclusion criteria	MRI protocol and region	MRI methods	DXA/QCT(DEXA scores)	Mean MRI-DEXA interval	Corelation coefficient (MRI vs BMD)
Yeung et al	Prospective observational	2005	53 (+12 young controls)	Postmenopausal women; mean age ~70 y	Inclusion: postmenopausal women undergoing DXA; Exclusion: metabolic bone disease, contraindications to MRI	1.5 T MRI; lumbar spine	^{1}H-MRS (fat content, fat unsaturation index)	DXA (T-score groups)	≤ 2 weeks	Fat content vs BMD: inverse ($r_s \approx -0.53$ with unsaturation index)
Griffth et al	Prospective cohort	2006	103	Women > 65 y; mean age 73 y	Inclusion: postmenopausal women; Exclusion: metabolic bone disease, spinal surgery, malignancy	1.5 T MRI; L1–L4	^{1}H-MRS, DWI, DCE-MRI	DXA (T-score classification)	Mean 11 days	Marrow fat ↑ with ↓BMD (significant inverse association)
Kim et al	Retrospective diagnostic study	2017	38 (44 vertebrae)	17 M / 21 F; mean age 63 y	Inclusion: acute vertebral fractures; Exclusion: metal implants, poor image quality	3 T MRI; fractured vertebrae	Six-echo Dixon FF (T2*-corrected)	DXA (T-score reference)	Same clinical episode	FF significantly higher in osteoporotic fractures (AUC 0.98)
Chang et al	Prospective observational	2020	76	Mixed sex adults	Inclusion: suspected OP; Exclusion: severe spinal pathology	3 T MRI; lumbar spine	^{1}H-MRS, mDIXON-Quant FF	QCT (vBMD)	Same visit	FF vs BMD: negative correlation ($p < 0.05$)

Gassert et al	Prospective matched cohort	2022	52	Mean age ~67 y; 62–70% women	Inclusion: patients with/without vertebral fractures; Exclusion: malignancy	3 T MRI; lumbar spine	Chemical-shift MRI PDFF	QCT (trabecular BMD)	Same visit	PDFF vs BMD: r = −0.51
Li et al	Prospective observational	2022	105	Postmenopausal women	Inclusion: postmenopausal; Exclusion: metabolic bone disease, spinal lesions	3 T MRI; L3	T2*-corrected Q-Dixon, IVIM	QCT (vBMD)	Same visit	FF vs BMD: r = −0.747; T2* vs BMD: r = −0.498
Watanabe et al	Retrospective feasibility study	2022	104	Men with prostate cancer	Inclusion: pelvic MRI + DXA; Exclusion: bone metastasis	3 T MRI; proximal femur	IDEAL-IQ (PDFF, R2*)	DXA (total hip T-score)	Same visit	R2* vs BMD: r = 0.60; PDFF: NS
Tang et al	Prospective observational	2023	138	Male adults	Inclusion: ≥18 y; Exclusion: metabolic bone disease, spine lesions	3 T MRI; lumbar spine	mDIXON-Quant FF, T2*	DXA + QCT	Same visit	FF vs vBMD: r = −0.604; T2* vs vBMD: r = −0.444
Zhou et al	Prospective cross sectional	2023	174	105 F / 69 M; > 30 y	Inclusion: same-day MRI & DXA; Exclusion: spinal disease	3 T MRI; lumbar spine	IDEAL-IQ FF, R2*	DXA (aBMD)	Same day	FF vs aBMD: r = −0.638 (women); R2* vs aBMD: r = 0.35 (men)
Naik et al	Cross-sectional observational	2023	31	Mean age 54 y; mixed sex	Inclusion: suspected OP; Exclusion: trauma, neoplasm	3 T MRI; lumbar spine	Dixon FF	DXA (T-score)	Same visit	FF vs T-score: inverse; AUC 0.925

R2* and Iron-Corrected Fat Metrics (Table 2)

Four studies evaluated R2* and iron-corrected fat metrics (17,23,25,26). R2* demonstrated independent associations with BMD, and combined multiparametric models incorporating fat fraction and R2* improved discrimination between osteopenia and osteoporosis compared with fat fraction alone. These findings suggest complementary biological information related to trabecular interfaces and marrow composition.

Table 2: R2and Iron-Corrected fat metrics:

Principal author	**Study design**	**year**	**N (patients)**	**Patient demographics**	**Inclusion/exclusion criteria**	**MRI protocol & region**	**MRI quantitative**	**DEXA/QCT reference**	**MRI DEXA/QCT interval**	**Corelation coefficient (MRI vs BMD)**

							methods			
Li et al	Prospective observational	2022	105	Postmenopausal women	Inclusion; postmenopausal women undergoing MRI &QCT Exclusion: spinal pathology, metabolic bone ds, contraindications to MRI	3.0TMRI; L3 vertebra; T2★-corrected Q-Dixon + reduced-FOV IVIM	FF, T2★,IVIM (Dslow,f)	QCT (vBMD)	Same visit	FF vs BMD: r = ─0.747; T2★vs BMD: r=─0.498; Dslow vs BMD: r = 0.659
Liu et al	Prospective observational	2023	83(415 vertebrae)	Mean age 59.8± 7.5y; 30M/53F; chronic low back	Inclusion: age ≥ 50y; lumbar MRI and QCT within 48 h. Exclusion: scoliosis, focal osteosclerosis, trauma, tumor, metabolic disease, postoperative spine	3.0 T MRI; lumbar spine(L1-L5); IDEAL-IQ seq	Fat Fraction (FF), R★relaxation rate	QCT (vBMD; mg/cm3)	≤48h	FF vs BMD: r= ─ 0.624; R2★vs BMD: r= 0.290
Zhou et al	Prospective cross sectional	2023	174	Mean age 53.6± 12.1 y;69 M/105F	Inclusion: age>30 y; same day DXA & MRI Exclusion: vertebral tumor, infection, surgery metabolic/endocrine bone disease, bone active drugs	3.0 T MRI; lumbar spine(L1-L3); IDEAL-IQ seq	FF, R2★	DXA (aBMD, T-score)	Same day	FF vs aBMD: r ~ ─0.515 to ─0.638(stronger in women); R2★ vs aBMD; r~0.19-0.35(Sex dependent)
Shan et al	Prospective clinical reproducible study	2022	48 (healthy volunteers)	Women only; mean age 51.9± 11.8 y	Inclusion: Healthy adults. Exclusion: systemic disease, drug/alcohol abuse	3.0 T MRI; lumbar spine(L1-L5); multiple IDEAL-IQ parameter sets	FF, R2★ repeatability SNR, CNR	DXA (supportive not diagnostic endpoint)	Same session	Not designed for BMD corelation (ICC for FF =0.987; R2★ =0.721)

Diffusion and IVIM-Based Imaging (Table 3)

Five studies investigated diffusion-weighted imaging and IVIM parameters (5,9,12,29,31). Osteoporotic bone demonstrated lower diffusion coefficients and perfusion fractions, reflecting microvascular and trabecular alterations. IVIM-derived parameters (D, D*, and f) showed variable but supportive correlations with bone density and marrow perfusion.

Table 3: Diffusion and IVIM-Based Imaging:

Author	Study design	Year	Total N	Patient demographics	Inclusion Exclusion criteria	MRI protocols and regions	MRI methods	DEXA scores/reference	Mean MRI-DEXA interval	Corelation coefficient (MRI vs DEXA/QCT)
Griffith et al	Prospective cohort	2006	103	Postmenopausal women; mean age 73 y (67–84)	Inclusion: women >65 y with DXA; Exclusion: metabolic bone disease, malignancy, spinal surgery, MRI contraindications	1.5 T MRI; lumbar spine (L3 or L2)	^{1}H-MRS (marrow fat), DWI (ADC), DCE-MRI (perfusion)	DXA (T-score; WHO criteria)	Mean 11 days (9–13)	Marrow fat ↑ with ↓BMD (significant inverse association); ADC not correlated
Koyama et al	Prospective observational	2013	16 subjects (48 vertebrae)	8 healthy men, 8 osteoporotic patients	Inclusion: subjects with DEXA and MRI; Exclusion: not specified	1.5 T MRI; L2–L4	T1WI, FS-T2WI SNR, DWI-ADC	DXA (BMD-based grouping)	Same visit	T1WI vs BMD: r = −0.64; FS-T2WI r = −0.36; ADC r = −0.29
Wu et al.	Prospective diagnostic	2019	28	Mean age 55 y; mixed sex	Inclusion: bone lesions in patients with tumors; Exclusion: typical metastases, MRI contraindications	3.0 T MRI; appendicular skeleton	IVIM-DWI, DKI	Not assessed (no DXA)	NA	Not applicable (study not designed for BMD correlation)
Yang et al.	Prospective observational	2024	135	54 M / 81 F; mean age 61.7 y	Inclusion: DXA + MRI; Exclusion: fractures, tumors, bone-active drugs	3.0 T MRI; lumbar spine (L1–L4)	IDEAL-IQ (FF, R2*), IVIM-DWI (D, D*, f, DDC)	DXA (T-score)	Same visit	FF vs BMD: r = −0.313; R2* vs BMD: r = 0.327; D vs BMD: r = 0.532

Shi et al	Prospective cross-sectional	2025	346	232 F / 114 M; mean age 67.7 y	Inclusion: age > 50 y, DXA + MRI within 1 week; Exclusion: metabolic bone disorders, poor image quality	3.0 T MRI; lumbar spine (L1–L4)	IDEAL-IQ (FF, R2*), IVIM-DWI (ADC slow, ADC fast, f)	DXA (T-score, BMD)	≤ 1 week	FF vs BMD: r = −0.402; ADC slow vs BMD: r = 0.494; R2* vs BMD: r ≈ 0.18

Composite and Opportunistic MRI Scores (Table 4)

Four studies evaluated composite MRI-derived metrics, primarily the vertebral bone quality (VBQ) score (13,16,21,27). VBQ demonstrated moderate inverse correlation with DXA BMD and high inter- and intra-rater reliability. Several studies reported VBQ as an independent predictor of fragility fractures, supporting its role in opportunistic osteoporosis screening during routine spine MRI.

Reference and Epidemiologic Context: There were four studies reviewed for referencing and epidemiologic context (1,3,6,11). These studies confirm DXA as the reference standard but also acknowledge MRI's growing role in bone quality assessment beyond density alone.

Table 4: Composite and Opportunistic MRI Scores

Author	**Study design**	**year**	**Total N**	**Patient demographics**	**Inclusion/ exclusion Criteria**	**MRI Protocols and regions**	**MRI methods**	**DEXA scores / reference**	**Mean MRI–DEXA interval**	**Correlation coefficient (MRI vs DEXA)**
Schilling et al	Retrospective reliability study	2021	30	Mixed sex; degenerative & oncologic spine patients	Inclusion: lumbar MRI available; Exclusion: not specified	3.0 T MRI; lumbar spine (L1–L4)	VBQ score (T1-weighted signal intensity ratios)	Not assessed	NA	Not assessed (study focused on inter-/intrarater reliability; ICC 0.67–0.96)
Kadri et al	Retrospective diagnostic study	2021	83	Mean age 70.1 y; 80% women	Inclusion: age ≥ 50 y, thoracolumbar MRI; Exclusion: incomplete imaging	1.5–3.0 T MRI; thoracolumbar spine (L1–L4)	VBQ score, single-level VBQ, VBQ(fat)	DXA (clinical osteoporosis diagnosis)	Same clinical episode	VBQ vs DXA-defined osteoporosis: AUC 0.806 (correlation coefficient not directly reported)
Ehresman et al	Retrospective cohort	2022	184	Patients with osteopenia/osteoporosis; metabolic bone clinic	Inclusion: DXA + lumbar MRI, ≥2-year follow-up; Exclusion: incomplete data	MRI (field strength not specified); lumbar spine	VBQ score (T1-weighted MRI)	DXA (T-score)	Same visit	VBQ significantly associated with fracture risk; DXA BMD not predicti

										ve (direct r not primary endpoint)
Pu et al	Retrospective observational	2023	100	Asian women; mean age 66.1 ± 9.4 y	Inclusion: age > 50 y, lumbar MRI & DXA; Exclusion: vertebral fracture ≥ grade II, spinal lesions, metabolic bone disease	1.5 T MRI (subset 3 T); lumbar spine (L1–L4)	VBQ score (overall & single-level)	DXA (lowest T-score reference)	Mean 3.4 ± 6.8 days	VBQ vs lowest DXA T-score: r = −0.524
Pu et al (preoperative validation)	Retrospective diagnostic validation	2023	100 (+24 interdevice controls)	Women undergoing lumbar spine surgery	Same as above	1.5 T & 3.0 T MRI; lumbar spine	VBQ score	DXA (T-score)	≤ 1 month	VBQ vs DXA T-score: r = −0.524; AUC for osteoporosis 0.81

DISCUSSION:

The collective purpose of the included studies was to evaluate magnetic resonance imaging (MRI)–derived quantitative and semi-quantitative biomarkers of vertebral bone quality and to determine their association with bone mineral density (BMD) measured by DXA or QCT, as well as their potential clinical utility for osteoporosis assessment, opportunistic screening, and fracture risk prediction. These studies aimed to address the known limitations of DXA by exploring MRI-based parameters that reflect bone marrow composition, trabecular microenvironment, and vertebral bone quality, without ionizing radiation.

1.Studies by Yeung et al. and Griffith et al. provided the pathophysiological foundation linking increased marrow adiposity with reduced BMD (4,5). These seminal studies demonstrated that osteoporosis is associated with a significant increase in vertebral marrow fat content and a shift toward more saturated lipids, measured using ^1H-MR spectroscopy. Griffith et al (5). further showed that declining BMD is accompanied by reduced vertebral marrow perfusion, while diffusion parameters remain largely unchanged, supporting a vascular–adipocytic mechanism underlying bone loss.

These findings provide the biological basis for MRI-based osteoporosis assessment and support marrow fat quantification as a radiation-free adjunct to DXA, enabling early detection of impaired bone quality on routine spine MRI.

2. Signal-based and diffusion MRI exploratory studies by Koyama et al. and Wu et al. aimed to explore whether conventional MRI signal intensity and diffusion parameters could reflect changes in bone density or microstructure (9,12). These studies assessed correlations between T1-weighted signal intensity, fat-suppressed sequences, ADC/IVIM parameters, and DXA-based BMD grouping. These studies also aimed to investigate the feasibility of diffusion-based techniques for bone quality assessment.

Across studies, MRI-derived parameters demonstrated the ability to reflect vertebral bone quality beyond DXA. Increased marrow fat content and reduced perfusion were consistently associated with lower BMD, while diffusion-based metrics showed variable but complementary value. Conventional signal-based MRI and IVIM-derived diffusion parameters correlated with bone density and microstructural changes, supporting MRI as a surrogate marker of skeletal integrity, particularly when densitometry is limited.

Clinical applications

These findings support opportunistic, radiation-free osteoporosis assessment during routine spine MRI and improved differentiation of benign, osteoporotic, and pathological marrow changes in clinical practice.

3.More recent Dixon- and IDEAL-IQ–based studies consistently confirmed that vertebral marrow fat fraction provides information beyond BMD alone (10,14,19,24,25,28–31). Multiparametric approaches combining fat fraction, diffusion, and susceptibility metrics further improved diagnostic discrimination. Across Dixon, mDIXON-Quant, IDEAL-IQ, and

PDFF techniques, vertebral fat fraction (FF/PDFF) shows a moderate-to-strong inverse correlation with DXA or QCT-derived BMD.

In contrast, R2* demonstrated weaker and sex-dependent associations with BMD, reflecting its sensitivity to trabecular interfaces and iron-related susceptibility rather than marrow fat alone.

The combination of FF with diffusion-based IVIM parameters further improved discrimination between osteopenia and osteoporosis, suggesting complementary biological information regarding marrow perfusion and cellularity (22).

Studies incorporating fracture endpoints further indicate that increased marrow fat is associated with bone fragility even when BMD differences are minimal, highlighting the limitation of densitometry alone. Methodological validation confirms good repeatability and feasibility of these sequences in routine clinical MRI, supporting their role as reliable quantitative biomarkers of bone quality. Importantly, technical validation studies confirmed the high repeatability and robustness of IDEAL-IQ fat quantification, supporting its feasibility for opportunistic and longitudinal osteoporosis assessment in routine spine MRI (23).

Clinical applications

Quantitative MRI enables opportunistic, radiation-free osteoporosis screening during routine spine or hip MRI, improves fracture risk stratification, and may complement DXA in equivocal or high-risk patients.

4.Vertebral Bone Quality (VBQ) score development and validation (2021–2023) studies by Ehresman, Schilling, Kadri, and Pu (13,16,21,27) focused on the VBQ score, an MRI-derived T1-signal-based metric to develop validate, and clinically evaluate the VBQ score as an opportunistic MRI screening tool for osteoporosis and fracture risk.

Recent studies evaluating the MRI-derived vertebral bone quality (VBQ) score demonstrate that simple T1-weighted signal–based metrics can reflect vertebral bone quality beyond DXA-derived BMD. VBQ showed a moderate inverse correlation with DXA T-scores and good diagnostic performance for identifying osteopenia and osteoporosis, with reproducible thresholds across studies. Importantly, VBQ was found to be an independent predictor of fragility fractures, outperforming BMD in fracture risk stratification, while reliability analyses confirmed good inter- and intra-rater agreement, supporting its robustness across readers and MRI systems.

Clinical applications

VBQ enables opportunistic, radiation-free osteoporosis screening on routine spine MRI, supports preoperative risk stratification, and helps identify patients requiring further densitometric evaluation.

Strengths and Limitations

A key strength of the available evidence is the consistency of directionality across studies, particularly the reproducible inverse association between vertebral marrow fat fraction and bone mineral density, as well as the demonstration that MRI-derived metrics such as the vertebral bone quality score can predict fragility fractures independently of DXA.

However, important limitations must be acknowledged. Most studies were single-centre and cross-sectional, with relatively small sample sizes and heterogeneous populations. MRI acquisition protocols, post-processing methods, reference standards (DXA vs QCT), and outcome measures varied substantially, limiting comparability across studies and precluding quantitative meta-analysis. Also, fracture outcomes and longitudinal treatment-response data were infrequently reported. These limitations highlight the need for standardised, multicentre prospective studies to strengthen the evidence base.

Future scope and directions for research

Large, multicentre prospective studies are required to validate MRI-derived biomarkers—fat fraction, diffusion parameters, R2*/T2*, and VBQ—across different scanners, field strengths, vendors, and ethnic populations. Standardisation of acquisition protocols, post-processing methods, and reporting thresholds is essential before routine clinical adoption.

The role of MRI in opportunistic screening, particularly in patients undergoing spine or hip imaging for non-osteoporotic indications, warrants cost-effectiveness and workflow-impact analyses.

Finally, emerging directions include machine learning–based risk stratification, correlation with biomechanical strength and histomorphometry, and exploration of MRI biomarkers in secondary osteoporosis and therapy monitoring, potentially positioning MRI as a comprehensive, radiation-free tool for skeletal health assessment.

CONCLUSIONS:

Across heterogeneous study designs and populations, vertebral marrow fat fraction demonstrated the most consistent inverse association with bone mineral density, while diffusion-based parameters and susceptibility metrics provided complementary but more variable correlations. Signal-based composite metrics such as the vertebral bone quality (VBQ) score showed moderate correlation with DXA and, importantly, independent predictive value for fragility fractures.

Collectively, the evidence supports MRI as a radiation-free adjunct to densitometry, capable of capturing aspects of bone quality not reflected by BMD alone. Future multicentre, longitudinal studies with standardised imaging protocols and fracture-based endpoints are required before MRI-derived biomarkers can be fully integrated into osteoporosis diagnostic pathways.

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