

ORIGINAL ARTICLE

Magnesium depletion score and its association with risk of cardiovascular mortality: systematic review and meta-analysis

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ABSTRACT

Background: The magnesium depletion score (MDS) combines diuretic use, proton pump inhibitor use, heavy alcohol consumption, and reduced kidney function as an indirect indicator of systemic magnesium status. We evaluated the association between MDS and cardiovascular disease (CVD) mortality.

Methods: Following PRISMA 2020, four databases were searched from inception through March 2025. Fully adjusted hazard ratios (HRs) were synthesized with inverse-variance random-effects models. Analyses were stratified according to whether the reference category was MDS = 0 or MDS = 0–1.

Results: Nine observational reports based on U.S. National Health and Nutrition Examination Survey cohorts met the eligibility criteria; eight contributed to quantitative synthesis. Among five reports using MDS = 0 as the reference, pooled HRs were 1.37 (95% CI, 1.11–1.69) for MDS = 1, 1.64 (95% CI, 1.28–2.10) for MDS = 2, and 2.59 (95% CI, 1.97–3.41) for the highest MDS category, with $I^2 = 0\%$ for each analysis. Among three reports using MDS = 0–1 as the reference, pooled HRs were 1.24 (95% CI, 1.01–1.54; $I^2 = 20\%$) for MDS = 2 and 1.84 (95% CI, 1.52–2.23; $I^2 = 0\%$) for the highest category.

Conclusions: Higher MDS was associated with greater CVD mortality, but the observational design, overlapping NHANES populations, indirect exposure definition, and residual confounding limit causal and predictive interpretation. Prospective external validation is required before MDS is adopted for clinical risk stratification.

Keywords: Cardiovascular mortality, magnesium depletion score, meta-analysis, NHANES, systematic review.

Introduction

Cardiovascular disease (CVD) comprises disorders of the heart and vascular system and remains a major cause of morbidity and mortality. In addition to established behavioral and metabolic risk factors, disturbances in mineral homeostasis may contribute to cardiovascular risk [1,2].

Magnesium influences vascular smooth-muscle tone, endothelial function, glucose and lipid metabolism, inflammation, platelet activity, and cardiac electrophysiology [3]. Low magnesium status has been associated with adverse outcomes in diabetes, heart failure, and stroke [4–6]. However, serum magnesium

represents only a small fraction of total-body magnesium and may not identify tissue depletion [7].

Renal magnesium reabsorption is affected by diuretic use, proton pump inhibitor use, heavy alcohol consumption,

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and impaired kidney function [7–9]. Fan et al. combined these four factors into the magnesium depletion score (MDS), which was evaluated against the magnesium tolerance test and subsequently examined in relation to inflammation and mortality [10]. Higher scores indicate a greater likelihood of systemic magnesium depletion, but the score remains an indirect exposure measure rather than a direct biomarker.

Individual observational studies have evaluated MDS in general and disease-specific NHANES cohorts, but their effect estimates, adjustment sets, and reference categories differ. We therefore systematically reviewed the evidence linking MDS with CVD mortality and synthesized fully adjusted estimates while preserving study-specific comparator definitions.

Methods

This systematic review and meta-analysis was reported in accordance with the PRISMA 2020 statement [11].

Data sources and search strategy

PubMed (MEDLINE), Scopus, Embase, and Web of Science were searched from database inception through March 2025 without date or language restrictions. The search combined terms for magnesium depletion or MDS with terms for CVD and cardiovascular mortality. The database-specific syntax and the yield from each database are reported in Supplementary Table S1. Reference lists of eligible reports were also checked.

Eligibility criteria

Eligible studies enrolled adults, measured or categorized MDS, reported CVD mortality, and provided a hazard ratio (HR) or sufficient data for effect estimation. Observational cohort, case-control, and randomized studies were eligible. Case reports, case series, reviews, books, editorials, and studies without CVD mortality data were excluded.

Study selection

Search results were imported into EndNote and then screened in Rayyan after duplicate removal. Six reviewers independently screened titles and abstracts. Potentially eligible reports underwent full-text review. Disagreements were resolved through discussion and, when necessary, consultation with a senior reviewer.

Data extraction and outcome definition

Two reviewers independently extracted the study year, NHANES cycles, target population, analytic sample, baseline demographic characteristics, MDS definition, reference category, follow-up, cardiovascular mortality definition, covariates, and adjusted HRs with 95% confidence intervals (CIs). Disagreements were resolved by a senior reviewer. When a report presented multiple overlapping cohorts, the broadest eligible cohort was selected. When several regression models were reported, the most fully adjusted model was selected. CVD mortality, as defined by each study using linked National Death Index records, was the primary outcome.

Quality assessment

Two reviewers independently assessed each report with the National Heart, Lung, and Blood Institute Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies [12]. Domain judgments were recorded as yes, no, cannot determine, not reported, or not applicable. Consistent with the tool guidance, domain responses were not converted into a numerical score. Overall ratings reflected the reviewers' judgment of internal validity, and disagreements were resolved by a third reviewer.

Statistical analysis

HRs were log-transformed, and standard errors were derived from the reported 95% CIs. Inverse-variance random-effects models used the DerSimonian-Laird estimator [13]. Statistical heterogeneity was summarized with Cochran's Q and Higgins' I^2 statistic [14]. Analyses were organized as MDS = 1, MDS = 2, and the highest reported MDS category. Because some studies used MDS = 0 as the reference and others used MDS = 0–1, estimates were stratified by reference category; no overall estimate across incompatible strata was emphasized. One study that compared MDS > 2 with MDS ≤ 2 was summarized narratively but not combined with category-specific analyses. Original analyses were prepared in Review Manager 5.4 [15]; during revision, model selection, calculations, and figures were independently reproduced using Python 3.12.13 (Python Software Foundation, Wilmington, DE, USA). Formal funnel-plot asymmetry tests were not performed because fewer than 10 studies contributed to each analysis.

Results

Search results

The database searches identified 190 records: PubMed ($n = 46$), Scopus ($n = 52$), Embase ($n = 65$), and Web of Science ($n = 27$). After removal of 59 duplicates, 131 titles and abstracts were screened; 122 were excluded. Nine full-text reports were assessed, and all nine met the eligibility criteria [10,16–23]. Eight reports contributed to the category-specific quantitative syntheses. The CKD report by Yin et al. [23] used a non-comparable dichotomous contrast (MDS > 2 vs. MDS ≤ 2) and was summarized narratively (Figure 1).

Study characteristics

All nine reports were observational analyses of U.S. NHANES cohorts. Populations included general adults and participants with CVD, chronic kidney disease, hypertension, diabetes, MASLD or MetALD, asthma, diabetic kidney disease, or stroke. The reports frequently used overlapping NHANES cycles and clinical subgroups; their sample sizes therefore do not represent independent or unique participants and were not summed. Study characteristics and the analytic samples used for cardiovascular mortality are shown in Table 1.

BMI, body mass index; CKD, chronic kidney disease; CVD, cardiovascular disease; DKD, diabetic kidney

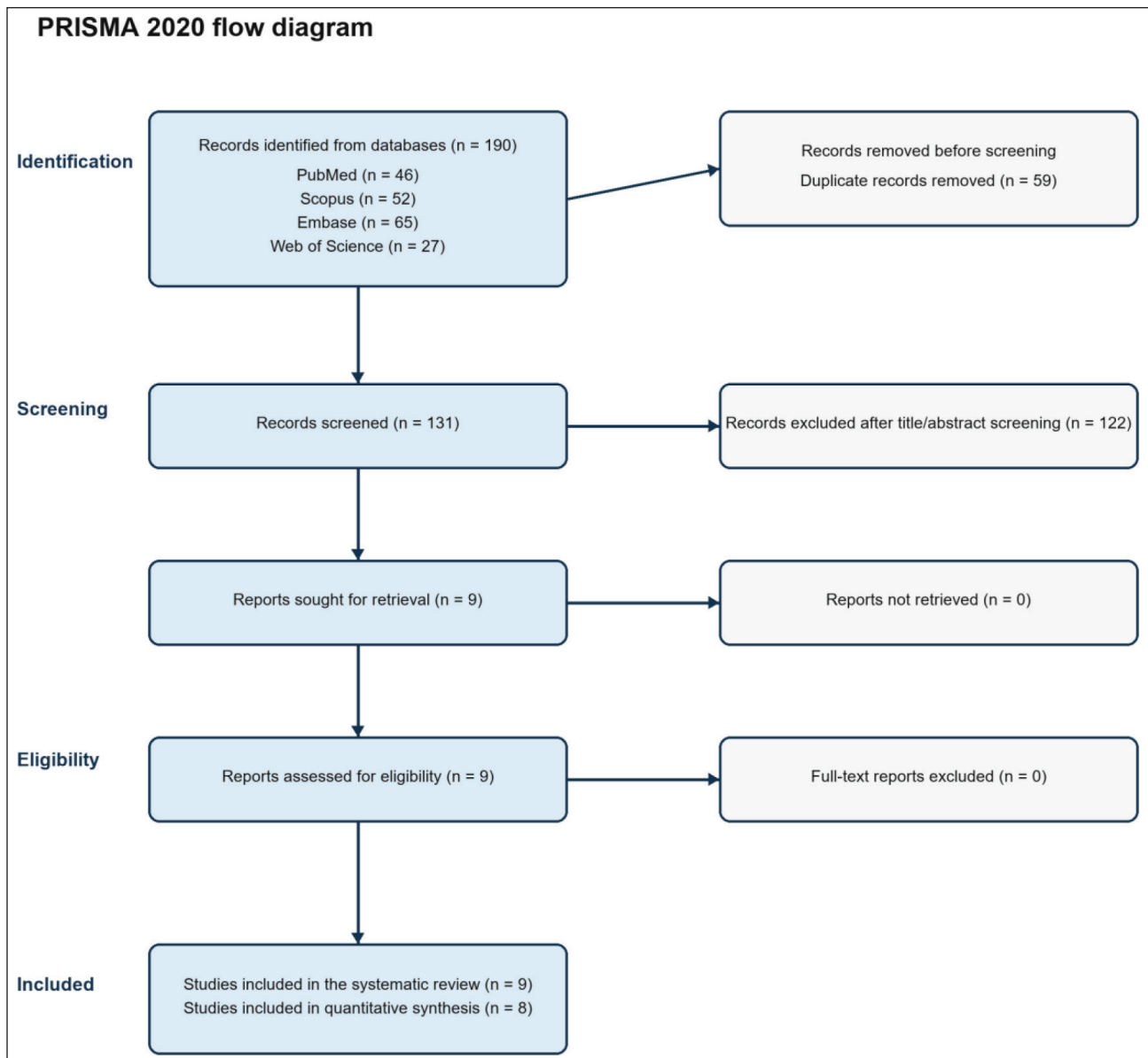


Figure 1. PRISMA 2020 flow diagram of study selection.

disease; MASLD, metabolic dysfunction-associated steatotic liver disease; MetALD, metabolic and alcohol-associated liver disease; MDS, magnesium depletion score; NHANES, National Health and Nutrition Examination Survey; NR, not reported. *The parent CKD cohort included 4,322 participants; 3,294 contributed to the cardiovascular-specific competing-risk analysis. †The parent DKD cohort included 3,199 participants; 3,195 had mortality follow-up. Because several reports used overlapping NHANES cycles and clinical subgroups, sample sizes must not be interpreted as unique participants or summed across reports.

Quality assessment

All reports clearly stated their objectives, defined the study populations and MDS exposure, used linked mortality outcomes, and adjusted for key confounders. Common limitations were a single baseline measurement of MDS, incomplete reporting of participation or linkage

rates, and the inability to blind outcome assessment in a conventional sense. Overall quality was judged good, with domain-level judgments reported in Supplementary Table S2.

Quantitative synthesis

MDS = 1 versus MDS = 0

Five reports provided fully adjusted estimates for MDS = 1 compared with MDS = 0. The pooled HR for CVD mortality was 1.37 (95% CI, 1.11–1.69), with no detected heterogeneity ($I^2 = 0\%$; Figure 2).

MDS = 2

Among five reports using MDS = 0 as the reference, MDS = 2 was associated with higher CVD mortality (HR, 1.64; 95% CI, 1.28–2.10; $I^2 = 0\%$). Among three reports using MDS = 0–1 as the reference, the pooled

Table 1. Characteristics of the included study reports and mortality cohorts

Study	Population	NHANES cycles	Mortality sample, n	Age, y	Women, %	BMI, kg/m ²	MDS categories (reference)
Fan et al., 2021 [10]	General U.S. adults	2005–2014	11,693	48.0	53.0	NR	0, 1, 2, >2 (0)
Ye et al., 2023 [19]	Adults with CVD	1999–2018	5,011	64.57	45.78	30.39	0, 1, 2, ≥3 (0)
Yin et al., 2023 [23]	Adults with CKD	1999–2014	3,294*	NR overall	53.5	NR overall	≤2, >2 (≤2)
Song et al., 2024 [22]	Adults with hypertension	2003–2018	12,485	57.36	50.15	30.99	0–1, 2, 3–5 (0–1)
Zhang et al., 2025 [20]	Adults with diabetes	1999–2018	5,219	59.26	49.65	33.11	0–1, 2, 3–5 (0–1)
Fan et al., 2025 [21]	MASLD or MetALD	NHANES III	3,802	NR overall	53.3	NR overall	0, 1, 2, >2 (0)
Fan et al., 2025 [16]	Adults with asthma	2005–2018	4,757	45.42	58.89	30.33	0, 1, 2, ≥3 (0)
Zhou and Yao, 2025 [17]	Adults with DKD	1999–2018	3,195†	63.98	48.70	32.78	0, 1, 2, ≥3 (0)
Yuan et al., 2025 [18]	Adults with stroke	1999–2018	1,751	64.24	56.43	29.90	0–1, 2, 3–5 (0–1)

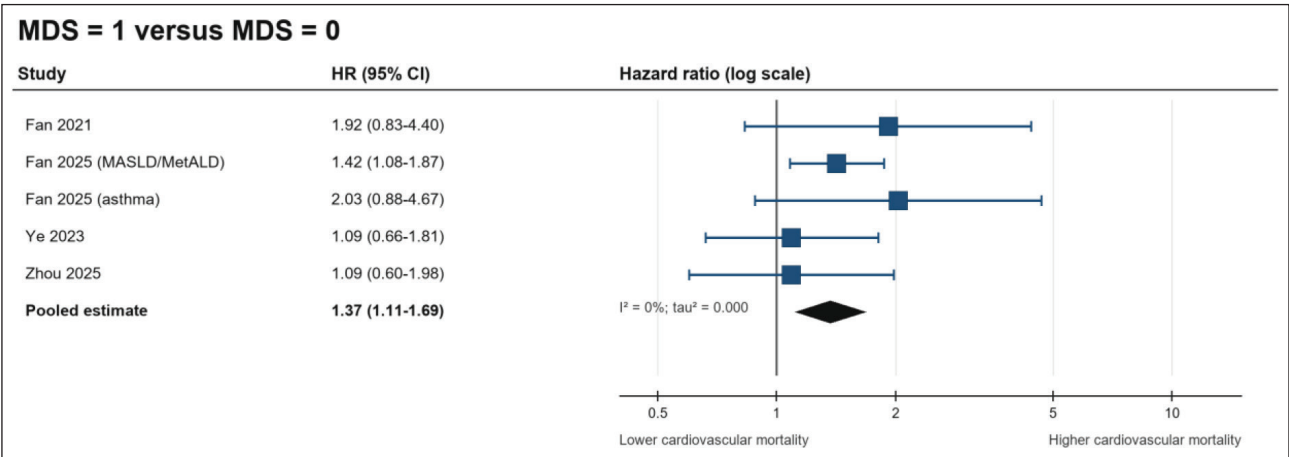


Figure 2. Random-effects meta-analysis of CVD mortality for MDS = 1 versus MDS = 0.

HR was 1.24 (95% CI, 1.01–1.54; *I*² = 20%). The strata were not combined because their comparator definitions differed (Figure 3).

Highest MDS category

Among five reports using MDS = 0 as the reference, the highest category (MDS ≥3 or >2) was associated with higher CVD mortality (HR, 2.59; 95% CI, 1.97–3.41; *I*² = 0%). Among three reports using MDS = 0–1 as the reference, the pooled HR was 1.84 (95% CI, 1.52–2.23; *I*² = 0%) (Figure 4).

Yin et al. [23] reported that MDS > 2 versus MDS ≤ 2 was independently associated with cardiovascular-specific mortality in adults with CKD (fully adjusted HR, 1.33; 95% CI, 1.06–1.66). This estimate was not pooled because its reference category incorporated MDS values of 0, 1, and 2.

Discussion

Main findings

This review found a graded association between higher MDS and CVD mortality across nine observational NHANES-based reports. When studies using MDS = 0 as the reference were analyzed together, the pooled association increased from HR 1.37 for MDS = 1 to HR

2.59 for the highest category. Studies using MDS = 0–1 as the reference showed smaller but directionally consistent associations. These results support an association but do not establish causality or validate MDS as a clinical prediction instrument.

Comparison with prior evidence and potential mechanisms

Magnesium deficiency has been linked to endothelial dysfunction, vascular calcification, inflammation, oxidative stress, hypertension, arrhythmia, and impaired glucose metabolism [24–28]. These pathways are biologically compatible with greater cardiovascular risk. Magnesium supplementation has influenced inflammatory and arrhythmic outcomes in some studies [29–31], but intervention evidence is not sufficiently consistent to infer that treating a high MDS will reduce mortality.

Earlier meta-analyses of dietary, circulating, and supplemental magnesium reported heterogeneous associations with cardiovascular outcomes [32–34]. MDS differs from a serum or intake measure because it combines factors that influence renal handling of magnesium. This may capture clinically relevant depletion risk, but it also embeds comorbidity and medication exposure within the score. Associations may therefore reflect both magnesium status and the

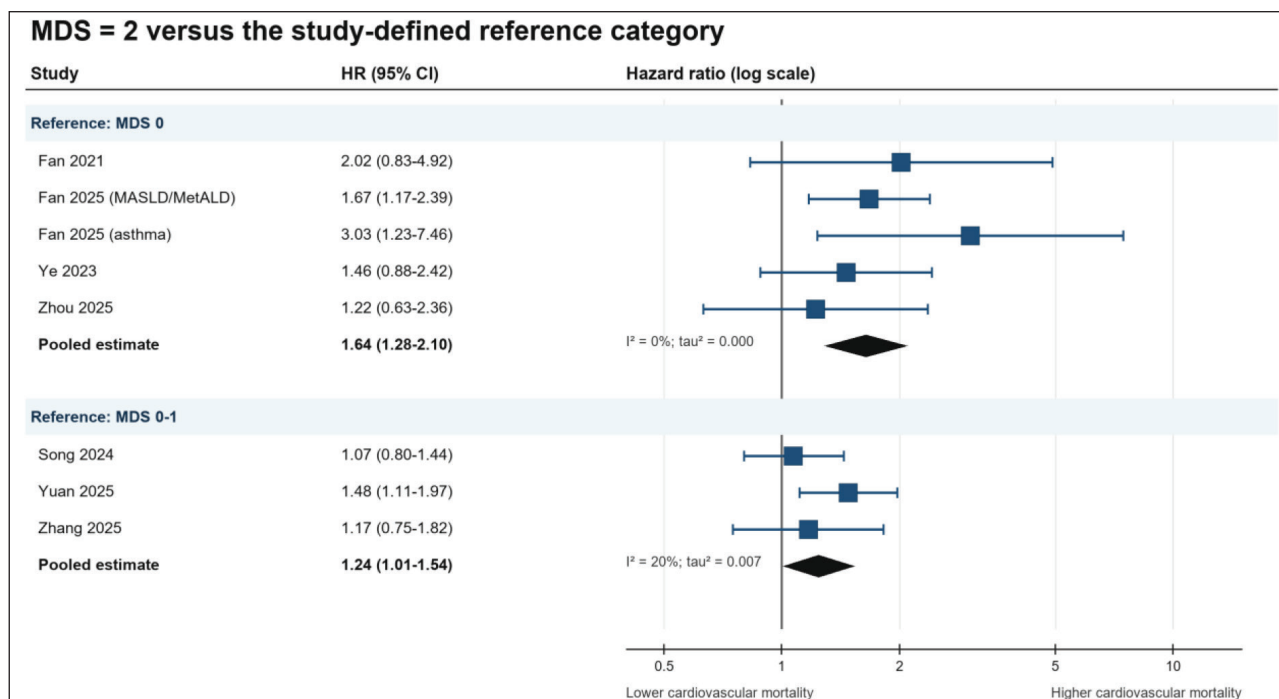


Figure 3. Random-effects meta-analysis of CVD mortality for MDS = 2, stratified by the study-defined reference category.

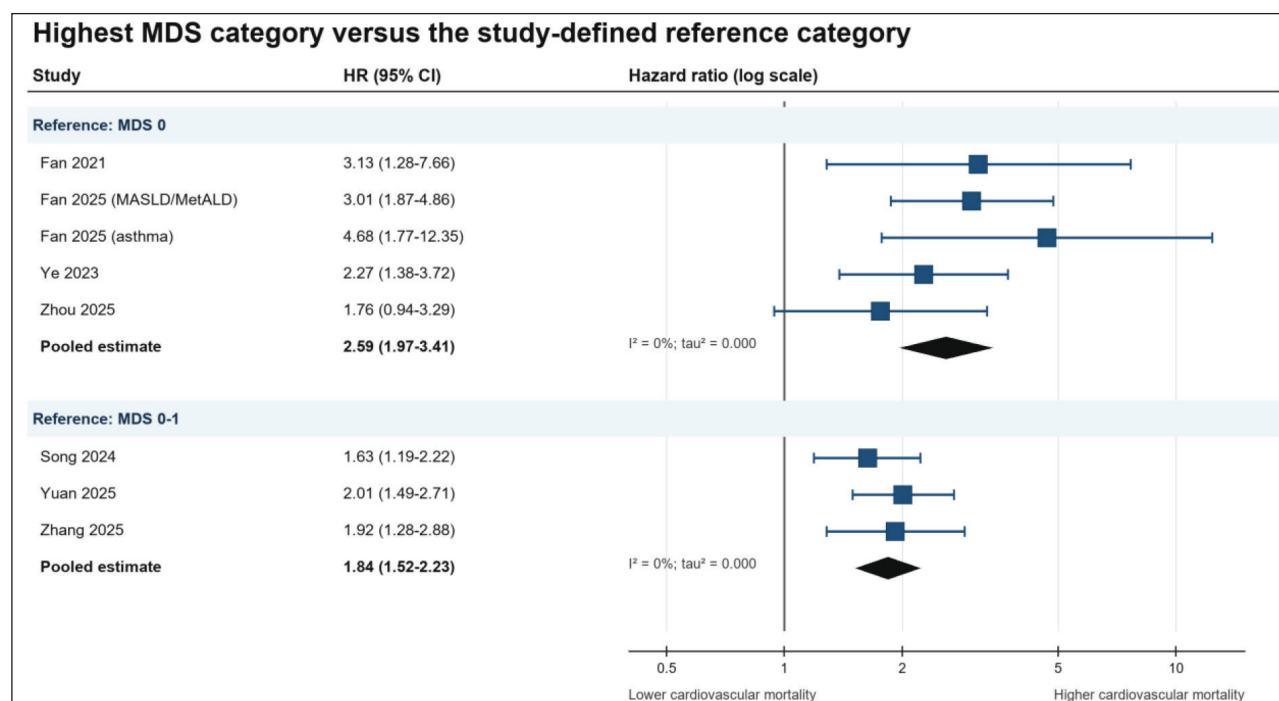


Figure 4. Random-effects meta-analysis of CVD mortality for the highest MDS category, stratified by the study-defined reference category.

prognostic effects of kidney dysfunction, diuretic use, proton pump inhibitor use, alcohol exposure, or their indications.

Clinical implications

MDS is inexpensive and can be calculated from routinely available information. Higher MDS has been associated with hypertension [35], although an earlier study found

no association between serum magnesium and the risks of hypertension or CVD [36], underscoring that MDS and serum magnesium are not interchangeable exposure measures. MDS has also been associated with metabolic syndrome, heart failure, vascular calcification, and mortality, suggesting potential value for risk enrichment [37–39]. Nevertheless, the present evidence does not support using MDS alone to guide magnesium supplementation or cardiovascular treatment. External

validation should evaluate discrimination, calibration, incremental value beyond established risk factors, and whether repeated assessment improves prediction [40,41].

Strengths and limitations

Strengths of this revision include source-level verification of all nine reports, use of the most fully adjusted estimates, separation of incompatible reference categories, and transparent reporting of the study that could not be pooled. Several limitations remain. All included reports were observational and U.S.-based, so residual confounding and limited generalizability are unavoidable. MDS is an indirect and usually single-time-point measure of magnesium status. Dietary magnesium, other medications, and comorbidity severity may not have been measured or modeled uniformly. Most importantly, several reports used overlapping NHANES cycles and clinical populations, violating strict independence between study-level estimates and potentially producing CIs that are too narrow. The small number of reports precluded reliable assessment of funnel-plot asymmetry or publication bias. These limitations require cautious interpretation of the apparent graded association.

Conclusions

Higher MDS was associated with greater CVD mortality in observational NHANES cohorts, with the largest association observed in the highest MDS category. The association persisted after restricting extraction to fully adjusted models and separating studies by reference definition. However, overlapping populations, indirect exposure measurement, and residual confounding limit causal and predictive conclusions. Prospective, multiethnic studies with independent cohorts and repeated magnesium assessment are needed before MDS is used for clinical risk stratification or treatment decisions.

Acknowledgments

None.

List of Abbreviations

BMI	Body mass index
CI	Confidence interval
CKD	Chronic kidney disease
CVD	Cardiovascular disease
DKD	Diabetic kidney disease
HR	Hazard ratio
MASLD	Metabolic dysfunction-associated steatotic liver disease
MDS	Magnesium depletion score
MetALD	Metabolic and alcohol-associated liver disease
NHANES	National Health and Nutrition Examination Survey
NR	Not reported
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Conflict of interest

The authors declare no competing interests.

Generative AI statement

During revision, the authors used OpenAI Codex (OpenAI, San Francisco, CA, USA) for language editing, source cross-checking, document formatting, and independent computational verification. The authors reviewed and verified all outputs, made all scientific decisions, and accept full responsibility for the manuscript.

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Clinical trial number

Not applicable.

Data availability

Study-level data used in the revised synthesis are reported in the included articles and Supplementary Table S3.

[Supplementary content \(If any\) is available online.](#)

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