Efficacy of narrow-diameter implants in restoring dentition defects in patients with diabetes: A systematic review and meta-analysis

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Abstract. The aim of the present study was to systematically evaluate the efficacy of narrow-diameter implants (NDIs) for restoring dentition defects in patients with diabetes and compare their clinical/radiographic outcomes with patients without diabetes (controls). Databases (PubMed, Embase, Web of Science, Cochrane Library and Google Scholar) were searched (January 1, 2000-July 15, 2025) for studies comparing NDI outcomes between patients with and without diabetes. The methodological quality and risk of bias of the included studies were assessed using the Newcastle-Ottawa Scale and the Joanna Briggs Institute Critical Appraisal Checklist. Meta-analysis was performed using RevMan v5.4 software. The nine included studies (410 patients; 688 implants) demonstrated high overall methodological quality. There was no significant intergroup difference in the survival rate [risk ratio (RR)=1.00; 95% confidence interval (CI) 0.93, 1.07; P=1.00]. Regarding radiographic outcomes, the diabetic group exhibited greater distal bone loss [mean difference (MD)=0.28 mm, 95% CI 0.02, 0.5; P=0.03), whereas the mesial bone level (MD=0.31 mm; P=0.08] and overall marginal bone level (MD=-0.02 mm; P=0.83) showed no significant differences. Furthermore, the diabetic group had markedly higher long-term (≥3 years) probing depth (MD=0.31 mm; P<0.0001), bleeding on probing (MD=14.41%; P=0.02), and plaque index (MD=13.77%; P=0.04). There was notable heterogeneity among the studies included in the meta-analysis, suggesting that individual studies may have influenced the overall findings. NDIs demonstrated satisfactory short-term survival in patients with diabetes. However, diabetes markedly increased long-term peri-implant inflammation risk and distal bone resorption, necessitating enhanced postoperative monitoring and personalized maintenance.

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Introduction

The rising global prevalence of diabetes mellitus (DM) has attracted increasing attention to oral health challenges in patients with diabetes, particularly in the context of dentition defect rehabilitation. As conventional prosthetic approaches often fail to meet both functional and aesthetic demands, implant-supported restorations have emerged as a preferred treatment option due to their superior biocompatibility and functional restoration capabilities (1). Narrow-diameter implants (NDIs) have gained prominence in the field of implant dentistry due to their unique clinical advantages, being particularly suitable for anatomically constrained sites, such as narrow alveolar ridges in the anterior region or limited posterior interdental spaces (2). Compared with standard-diameter implants, NDIs reduce or may even eliminate the need for complex bone augmentation procedures, thereby minimizing surgical trauma, complication risk, and treatment duration (3). However, NDI efficacy in diabetic populations warrants careful evaluation.

Patients with diabetes present distinct challenges for implant rehabilitation because their pathophysiological alterations markedly impact long-term implant stability. Chronic hyperglycemia disrupts peri-implant tissue homeostasis via multiple mechanisms, including the accumulation of advanced glycation end products (AGEs), sustained proinflammatory responses, and microangiopathy, resulting in a dysregulated immune microenvironment, disordered bone metabolism, and impaired soft tissue healing (4,5). Furthermore, diabetes-induced changes in salivary composition and oral microbiota dysbiosis may exacerbate peri-implant inflammation (6).

Given these challenges, NDIs may offer a strategic advantage for patients with diabetes due to their minimally invasive nature and reduced bone volume requirements (7). Their smaller diameter reduces surgical trauma and postoperative infection risk, which are critical considerations for patients with impaired healing capacity (8). Furthermore, advanced NDI technologies, such as titanium-zirconium alloys and SLActive

hydrophilic surfaces, may partially mitigate diabetes-related osseointegration deficits (9).

Nevertheless, existing studies report conflicting outcomes. While some report 5-year survival rates (SRs) of 92.3% for NDIs in well-controlled cases of diabetes (HbA1c <7%), Alsahhaf *et al* (10) observed markedly elevated peri-implant inflammatory markers and marginal bone loss (MBL; 1.6-1.8 mm vs. 0.8-1.1 mm; P<0.05), even in optimally managed cases. Notably, previous systematic reviews have mainly focused on standard-diameter implants, leaving a critical knowledge gap regarding NDI performance in diabetic populations (1,3). The present study addresses this gap by conducting the first systematic evaluation of NDIs in patients with diabetes, using a time-stratified analysis (short-term: ≤1 year, medium-term: 1-3 years, and long-term: ≥3 years) to establish a multidimensional assessment framework incorporating clinical parameters [such as probing depth (PD), bleeding index and plaque index (PI)] and radiographic indicators (such as MBL). Its clinical implications are threefold: i) Providing evidence-based guidance for NDI applications in patients with diabetes, ii) facilitating personalized treatment plans based on glycemic control status and iii) optimizing postoperative maintenance protocols, thereby collectively contributing to enhanced long-term SRs of implant rehabilitation in this population.

Materials and methods

Data sources and search strategy. The present systematic review and meta-analysis were performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review protocol was not registered in PROSPERO, as data collection had commenced before the authors became aware of the importance of prospective protocol registration. Retrospective registration was considered but deemed not appropriate for the present study, given that data extraction and analysis had already been completed prior to submission. Prospective registration is intended to prevent selective reporting and promote transparency before the review process begins; retrospective registration would not fulfill this purpose. Instead, to maintain methodological rigor and transparency, the review was conducted and reported in accordance with the PRISMA 2020 guidelines. A comprehensive literature search of PubMed (https://pubmed.ncbi.nlm.nih.gov), Embase (https://www.embase.com), Web of Science (https://www.webofscience.com), Cochrane Library (https://www.cochranelibrary.com), and Google Scholar (https://scholar.google.com) databases was performed to identify studies published between January 1, 2000 and July 15, 2025, with the final search conducted across all databases on July 15, 2025. The search was restricted to English-language articles and customized for each database using medical subject headings (MeSH) terms and free-text keywords following the Patient (or Population), Intervention, Comparison, and Outcome framework. The core search structure was as follows.

PubMed. ('narrow-diameter implants' (MeSH) OR 'NDI' (Title/Abstract) OR 'small-diameter implants' (Title/Abstract) OR 'SDI' (Title/Abstract) OR 'mini implants' (Title/Abstract)) AND ('diabetes mellitus' (MeSH) OR 'diabetes' (Title/Abstract) OR 'diabetic' (Title/Abstract) OR 'HbA1c' (Title/Abstract) OR 'hyperglycemia' (MeSH) OR 'hyperglycemia' (Title/Abstract)) AND ('nondiabetic' (Title/Abstract) OR 'non-diabetes' (Title/Abstract) OR 'healthy controls' (Title/Abstract) OR 'systemically healthy' (Title/Abstract) OR 'euglycemic' (Title/Abstract) OR 'normoglycemic' (Title/Abstract)) AND ('implant survival' (Title/Abstract) OR 'success rate' (Title/Abstract) OR 'marginal bone loss' (Title/Abstract) OR 'MBL' (Title/Abstract) OR 'crestal bone level' (Title/Abstract) OR 'CBL' (Title/Abstract) OR 'peri-implant parameters' (Title/Abstract) OR 'probing depth' (Title/Abstract) OR 'PD' (Title/Abstract) OR 'bleeding on probing' (Title/Abstract) OR 'BOP' (Title/Abstract) OR 'plaque index' (Title/Abstract) OR 'PI' (Title/Abstract)).

Embase. Adapted using Emtree terms and free-text keywords, including 'narrow-diameter implant'/Explosion (exp), 'DM'/exp, and 'hyperglycemia'/exp, combined with the same keyword combinations in title/abstract fields.

Web of science. Topic field search using the same combination of free-text keywords.

Cochrane library. Title/Abstract/Keyword search using the same combination of free-text keywords.

Google scholar. A manual search was undertaken using simplified keyword combinations: 'NDIs' AND 'diabetes' AND 'clinical study'. The first 200 results were screened for relevance.

Two independent reviewers with expertise in systematic literature retrieval performed the search. Any discrepancies were resolved through discussion or consultation with a third reviewer.

Inclusion criteria. Studies were included if they met the following criteria: i) Population: adult patients (≥18 years old) with type 1 or type 2 diabetes receiving NDIs for tooth replacement. For this review, NDIs were defined as implants with a diameter ≤3.5 mm, consistent with the established literature (10). ii) Study design: Randomized controlled trials (RCTs), cohort studies, and cross-sectional studies were eligible for inclusion. iii) Intervention/comparison: Placement of NDIs in patients with diabetes vs. patients without diabetes OR comparison of diabetic subgroups (such as HbA1c ≤7% vs. >7%). iv) Outcomes: Implant SR, radiographic outcomes [MBL and mesial/distal crestal bone loss (CBL)], and soft tissue parameters [PD, bleeding on probing (BOP) and PI]. iv) Follow-up: Minimum 6 months post loading.

Exclusion criteria. Studies were excluded if they: i) Involved patients with uncontrolled systemic diseases (such as HbA1c >9%, severe immunocompromised conditions, or active periodontal disease) that could markedly impair healing. ii) Reported SR data without a clear definition of implant failure or survival, or did not specify whether the analysis was performed at the patient- or implant-level. iii) Used major bone augmentation procedures (such as block grafts and sinus lifts) in conjunction with NDI placement. iv) Lacked

sufficient outcome data (such as missing standard deviation values for continuous variables). v) Were case reports, case series (<10 patients per group), reviews, conference abstracts, or animal/*in vitro* studies.

Data extraction. Literature screening and data extraction were performed independently by two researchers in accordance with the inclusion/exclusion criteria. Titles and abstracts were screened, followed by a full-text review of eligible studies. Any disagreements were resolved through discussion or, if necessary, consultation with a third senior researcher. Extracted data included study characteristics (author, year, design, sample size and follow-up duration), implant site, implant details (diameter, length, and surface treatment), and outcomes (SR, CBL, MBL, PD, BOP and PI). For SR data extraction, the analysis unit (patient-level) was recorded, along with the number of patients with implant failure and the total number of patients in each group. When multiple follow-up time points were reported, the longest available follow-up data were extracted. For the outcome of MBL/CBL, measurement, differences across studies were managed by first prioritizing mesial and distal CBL data, as these sites were the most consistently reported. Second, when multiple time points were available, the longest follow-up data were extracted to ensure consistency in the long-term outcome assessment. Third, all MBL/CBL data were converted to millimeters (mm) for uniformity because all included studies reported measurements in mm. Fourth, for studies reporting mean MBL without separate mesial and distal values, the reported mean values were used in the analysis. For PD data extraction, the measurements were assessed at four or six sites per implant and extracted as patient-level mean values (mm). For BOP/PI data extraction, these parameters were assessed at the same sites as used for PD. For the meta-analysis, BOP and PI were extracted as patient-level percentages, which were derived from site-level assessments.

Quality assessment. The methodological quality of cohort studies was evaluated using the Newcastle-Ottawa Scale (NOS) (11), and that of cross-sectional studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist (12). Any discrepancies in quality ratings were resolved through discussion with a third independent reviewer to ensure objectivity and reliability in the assessment process.

Statistical analysis. Meta-analysis was performed using RevMan v5.4 software (Cochrane Collaboration). Continuous outcomes (CBL, MBL, PD, BOP and PI) were analyzed using MDs with 95% CIs. Dichotomous outcomes (SRs) were pooled as risk ratios (RRs). Model selection was based on heterogeneity levels: fixed-effects models were applied for low heterogeneity (I^2 <50%) and random-effects models for substantial heterogeneity (I^2 ≥50%). Sensitivity analysis was performed using the leave-one-out method to assess robustness. Publication bias was evaluated using funnel plots. A two-sided P-value <0.05 was deemed statistically significant.

Results

Literature search. The initial database search yielded 645 records, which were reduced to 457 after removing duplicates.

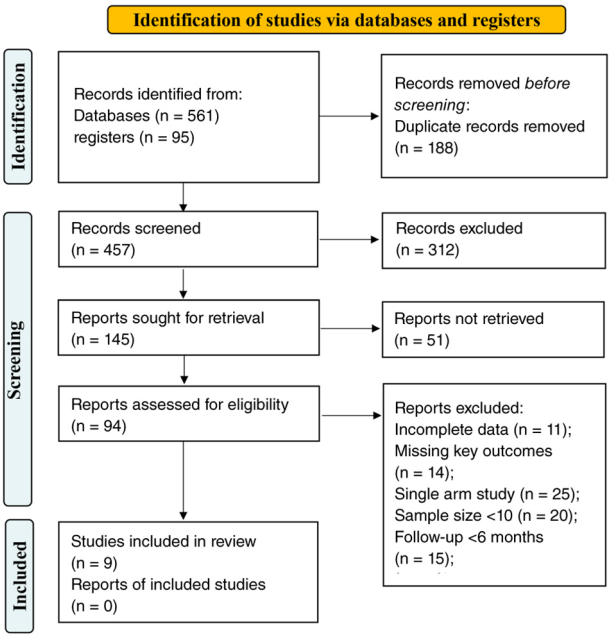

Figure 1. Flow chart for data search and gathering.

Following title/abstract screening, 312 articles were excluded due to irrelevant study designs, lack of control groups, or animal studies, leaving 145 for full-text review. Ultimately, nine studies met the inclusion criteria (10,13-20), comprising seven cohort studies (10,13,15-19) and two cross-sectional studies (14,20). No RCTs satisfying the inclusion criteria were identified. All nine included studies enrolled patients with type 2 DM; no studies involving patients with type 1 diabetes were identified. The 85 studies were excluded for the following reasons: incomplete data (n=11), missing key outcomes (n=14), single-arm study (n=25), sample size <10 (n=20), and follow-up <6 months (n=15; Fig. 1). The included studies (total: 410 patients; 688 implants) compared clinical outcomes of NDIs between patients with and without diabetes, reporting at least one of the following parameters: SR, MBL, CBL, PD, BOP and PI (Table I).

Quality evaluation. The methodological quality assessment revealed that the included cohort studies achieved a median NOS score of 7 (range: 6-8; Table II), indicating high overall quality. Furthermore, the two cross-sectional studies assessed using the JBI checklist were rated as high-quality, with scores of 8 and 7, respectively; Table III). Several patterns in risk of bias were observed across the included studies. Regarding selection bias, most studies had clearly defined inclusion criteria and recruited representative samples of patients with and without diabetes, although few explicitly reported whether sampling was consecutive or random. For comparability, most studies controlled for key confounders, including age, smoking and oral hygiene status, by matching or statistical adjustment. However, important diabetes-specific confounders, including duration of diabetes and glycemic control at the subgroup level (such as HbA1c ≤7% vs. >7%), were not consistently addressed. Regarding outcome measurements, all studies used objective clinical and radiographic parameters (PD, BOP, PI and CBL) with standardized protocols, although minor variations in

Table I. Basic information and relevant efficacy indicators of included studies.

Authors, year	Study design	Patients/ Total lessons		Implant location		Implant details		Follow up (m)	Survival rate		Marginal bone loss (mm)		Mesial CBL (mm)		Distal CBL (mm)		Probing depth (mm)		Bleeding on probing (%)		Plaque index (%)		(Refs.)
		DM	Non-DM	DM	Non-DM	DM	Non-DM		DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	
Alsahhaf *et al*, 2019	Retrospective cohort study	38/65	40/52	Anterior and posterior tooth regions	Anterior and posterior tooth regions	Diameter: 3.3 mm; Material: titanium	Diameter: 3.3 mm; Material: titanium	12	NR	NR	NR	NR	NR	NR	NR	NR	2.32±0.18	2.04±0.21	46±6	22±4	37±5	15±3	(10)
								18	NR	NR	NR	NR	0.1±0.05	0.11±0.08	0.34±0.13	0.31±0.13	2.35±0.22	2.11±0.2	49±5	25±5	40±4	18±2	
								36	NR	NR	NR	NR	0.11±0.08	0.12±0.1	0.46±0.16	0.41±0.13	2.39±0.18	2.18±0.18	53±7	21±6	42±6	17±3	
Alsahhaf *et al*, 2022	Cross-sectional study	30/92	30/86	Posterior jaws	Posterior jaws	Diameter: 2.9 mm; Length: 10 mm or 12 mm; Surface treatment: Moderately rough, platform-switched	Dia meter: 2.9 mm; Length: 10 mm or 12 mm; Surface treatment: Moderately rough, platform-switched	60	NR	NR	NR	NR	1.6±0.8	0.8±0.3	1.7±0.9	0.9±0.4	4±1.2	3.1±0.7	24.4±10.6	18.4±6.8	35.9±9.5	21.7±6.3	(14)
Alshahrani *et al*, 2020	Retrospective cohort study	25/25	25/25	NR	NR	Diameter: 3.2 mm; Length: 11.5 mm; Surface treatment: Moderately rough, tapered, platform-switched	Diameter: 3.2 mm; Length 11.5 mm; Surface treatment: Moderately rough, tapered, platform-switched	36	NR	NR	NR	NR	NR	NR	NR	NR	1.4±0.2	1.2±0.3	NR	NR	60±20	40±10	(15)

Table I. Continued.

Authors, year	Study design	Patients/ Total lessons		Implant location		Implant details		Follow up (m)	Survival rate		Marginal bone loss (mm)		Mesial CBL (mm)		Distal CBL (mm)		Probing depth (mm)		Bleeding on probing (%)		Plaque index (%)		(Refs.)
		DM	Non-DM	DM	Non-DM	DM	Non-DM		DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	
Al-Shibani *et al*, 2019	Prospective cohort study	22/22	25/25	Posterior mandible	Posterior mandible	Diameter: 3.3 mm; Length: 10 mm; Surface treatment: Moderately rough	Diameter: 3.3 mm; Length: 10 mm; Surface treatment: Moderately rough	18	NR	NR	NR	NR	NR	NR	NR	NR	2.21± 0.45	2.27± 0.31	23.61± 2.23	22.48± 2.8	24.37± 1.75	25.49± 2.16	(13)
								36	NR	NR	NR	NR	NR	NR	NR	NR	2.27± 0.31	2.48± 0.31	25.9± 2.93	20.84± 3.64	27.02± 1.99	28.15± 1.73	
Cabrera-Domíngue *et al*, 2017	Prospective cohort study	15/15	14/14	Anterior tooth area and premolar area	Anterior tooth area and premolar area	Diameter: 3.3 mm; Length: 10/12 mm; Surface treatment: Hydrophilic SLActive surface (sandblasting acid etching + chemical modification)	Diameter: 3.3 mm; Length: 10/12 mm; Surface treatment: Hydrophilic SLActive surface (sandblasting acid etching + chemical modification)	6	15/15	14/14	1.28± 0.38	1.11± 0.59	NR	NR	NR	NR	2.04± 0.66	2.07± 0.78	10.1± 9.09	13.8± 12.26	4.6± 4.47	6.77± 5.41	(16)
Cabrera Domíngue *et al*, 2020	Prospective cohort study	14/14	14/14	Canine area and premolar area	Canine area and premolarv area	Diameter: 3.3 mm; Length: 10/12 mm; Surface treatment: Hydrophilic SLActive surface	Diameter: 3.3 mm; Length: 10/12 mm; Surface treatment: Hydrophilic SLActive surface	6	14/14	14/14	0.48± 0.28	0.68± 0.54	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	(17)

Table I. Continued.

Authors, year	Study design	Patients/ Total lessons		Implant location		Implant details		Follow up (m)	Survival rate		Marginal bone loss (mm)		Mesial CBL (mm)		Distal CBL (mm)		Probing depth (mm)		Bleeding on probing (%)		Plaque index (%)		(Refs.)
		DM	Non-DM	DM	Non-DM	DM	Non-DM		DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	
								12	NR	NR	0.54± 0.6	0.64± 0.53	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	
								24	NR	NR	0.68± 0.67	0.75± 0.49	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	
Diehl *et al*, 2024	Prospective cohort study	11/16	15/16	Posterior tooth area (maxillary or mandibula)	Posterior tooth area (maxillary or mandibula)	Diameter: 3.3 mm; Length: 8, 10, 12 mm; Surface treatment: SLActive® Hydrophilic surface Material: ti-zr alloy Roxolid®	Diameter: 3.3 mm; Length: 8, 10, 12 mm; Surface treatment: SLActive® Hydrophilic surface Material: ti-zr alloy Roxolid®	24	11/ 11	15/ 15	0.09± 0.89	0.15± 0.83	NR	NR	NR	NR	2.4± 0.55	2.3± 0.71	NR	NR	NR	NR	(18)
								48	NR	NR	NR	NR	NR	NR	NR	NR	2.3± 0.77	2.3± 0.88	NR	NR	NR	NR	
Friedman *et al*, 2021	Prospective cohort study	13/13	16/16	Posterior tooth area (maxillary or mandibula)	Posterior tooth area (maxillary or mandibula)	Diameter: 3.3 mm; Length: 8, 10, 12 mm; Surface treatment: SLActive® Hydrophilic surface Material: ti-zr alloy (Roxolid®)	Diameter: 3.3 mm; Length: 8, 10, 12 mm; Surface treatment: SLActive® Hydrophilic surface Material: ti-zr alloy (Roxolid®)	3	NR	NR	NR	NR	NR	NR	NR	NR	2.7± 0.5	2.6± 0.8	NR	NR	NR	NR	(19)

Table I. Continued.

Authors, year	Study design	Patients/ Total lessons		Implant location		Implant details		Follow up (m)	Survival rate		Marginal bone loss (mm)		Mesial CBL (mm)		Distal CBL (mm)		Probing depth (mm)		Bleeding on probing (%)		Plaque index (%)		(Refs.)
		DM	Non-DM	DM	Non-DM	DM	Non-DM		DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	DM	Non-DM	
								12	13/13	13/13	0.65±1.34	0.01±0.83	NR	NR	NR	NR	2.6±0.4	2.4±0.5	NR	NR	NR	NR	
Tulbah *et al*, 2023	Cross-sectional study	31/82	32/96	Anterior mandible	Anterior mandible	Diameter: 2.9 mm; Length: 10 mm or 12 mm; Surface Treatment: Moderately rough, platform-switched	Diameter: 2.9 mm; Length: 10 mm or 12 mm; Surface Treatment: Moderately rough, platform-switched	120	NR	NR	NR	NR	1.67±0.08	1.13±0.03	1.59±0.09	1.19±0.06	3.9±0.5	3.3±0.4	26.8±6.3	12.3±2.6	36.7±8.1	25.4±5.8	(20)

DM, diabetes mellitus; CBL, crestal bone loss; NR, not reported; Ti-Zr, titanium-zirconium.

Table II. Newcastle-Ottawa Scale for cohort studies.

	Selection				Comparability	Exposure				
Authors, year	Is the case definition adequate?	Represen-tativeness of the cases	Selection of Controls	Definition of Controls	Comparability of cases and controls on the basis of the design or analysis	Ascertainment of exposure	Same method of ascer-tainment for cases and controls	Non-response rate	Scores	(Refs.)
Alsahhaf *et al*, 2019	★	★	★	★	★	★★	★		7	(10)
Alshahrani *et al*, 2020	★	★	★	★	★★	★		★	8	(15)
Al-Shibani *et al*, 2019	★	★	★	★	★	★★	★		7	(13)
Cabrera-Domínguez *et al*, 2017	★	★	★	★	★	★★			6	(16)
Cabrera-Domínguez *et al*, 2020	★	★	★	★	★	★★	★		7	(17)
Diehl *et al*, 2024	★	★	★	★	★		★★		6	(18)
Friedmann *et al*, 2021	★	★	★	★	★	★	★★		8	(19)

Table III. Joanna Briggs Institute Critical Appraisal Checklist for cross-sectional studies.

Authors, year	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured in a valid and reliable way?	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	Were the outcomes measured in a valid and reliable way?	Was appropriate statistical analysis used?	Scores	(Refs.)
Alsahhaf *et al*, 2022	1	1	1	1	1	1	1	1	8	(14)
Tulbah *et al*, 2023	1	1	1	1	0	1	1	1	7	(20)

measurement techniques (such as four vs. six sites for PD) and lack of blinding of outcome assessors to patient glycemic status may have introduced detection bias.

Diabetes markedly increased PD around NDIs. Pooled data from eight studies (total: 643 implants) revealed that patients with diabetes had higher PD values (MD=0.23 mm; 95% CI 0.15, 0.31; P<0.00001), with moderate heterogeneity (I^2=57%; random-effects model). Subgroup analysis demonstrated significant time-dependent effects. In the short-term group (≤1 year), the diabetic group showed higher PD values (MD=0.26 mm, 95% CI 0.18, 0.34; P<0.00001). In the medium-term group (1-3 years), there was no statistically significant intergroup difference (MD=0.11 mm; 95% CI-0.12, 0.34; P=0.34). In the long-term group (≥3 years), PD values became higher again in the diabetic group (MD=0.31 mm, 95% CI 0.16, 0.46; P<0.0001; Fig. 2). These findings indicate that longer follow-up may be associated with a trend toward greater differences in PD between patients with and without diabetes. However, the moderate heterogeneity warrants cautious interpretation.

Diabetes markedly increased long-term BOP around NDIs. Pooled data from six studies (total: 480 implants) demonstrated higher BOP in the diabetic group (MD=13.06%; 95% CI 4.58, 21.54; P=0.003), with extreme heterogeneity (I^2=99%; random-effects model). Subgroup analysis revealed key temporal patterns. There were no statistically significant intergroup differences in the short-term (≤1 year) and medium-term (1-3 years) groups (MD=10.40%, 95% CI-16.77, 37.57; P=0.45 and MD=12.55%; 95% CI-9.86, 34.96; P=0.27, respectively), but there was a significant increase in BOP in the long-term (≥3 years) diabetic group (MD=14.41%; 95% CI 2.37, 26.46; P=0.02), with consistent effect direction across all studies (Fig. 3). Notably, Alsahhaf *et al* (10,14) reported strong positive effects (MD=24-32%) across all subgroups, markedly influencing the pooled results. These findings suggested that diabetes primarily exerts long-term (≥3 years) adverse effects on BOP follow-up. However, the extreme heterogeneity indicates limited robustness of these results, warranting cautious interpretation in conjunction with sensitivity analyses.

Diabetes markedly increased PI around NDIs. Pooled data from seven studies (total: 530 implants) demonstrated higher overall PI in patients with diabetes (MD=12.15%; 95% CI 3.78, 20.52; P=0.004), with extreme heterogeneity (I^2=99%; random-effects model). Time-stratified analysis revealed that there were no significant intergroup differences in these short-term (≤1 year) and medium-term (1-3 years) groups (MD=9.97%; 95% CI-13.72, 33.65; P=0.41 and MD=10.44%; 95% CI-12.22, 33.09; P=0.37, respectively). However, there was a significant increase in PI in the long-term (≥3 years) diabetic group (MD=13.77%; 95% CI 0.54, 26.99; P=0.04), with 80% of studies supporting this finding (MD=17.57%; 95% CI 9.62, 25.53), except for Al-Shibani *et al* (13), who reported opposite results (MD=-1.13%; 95% CI-2.22, -0.06; Fig. 4). Although the overall effect was significant and most long-term studies supported a positive correlation between diabetes and plaque accumulation, the contradictory findings of Al-Shibani *et al* (13) and the extreme heterogeneity warrant cautious interpretation of these conclusions.

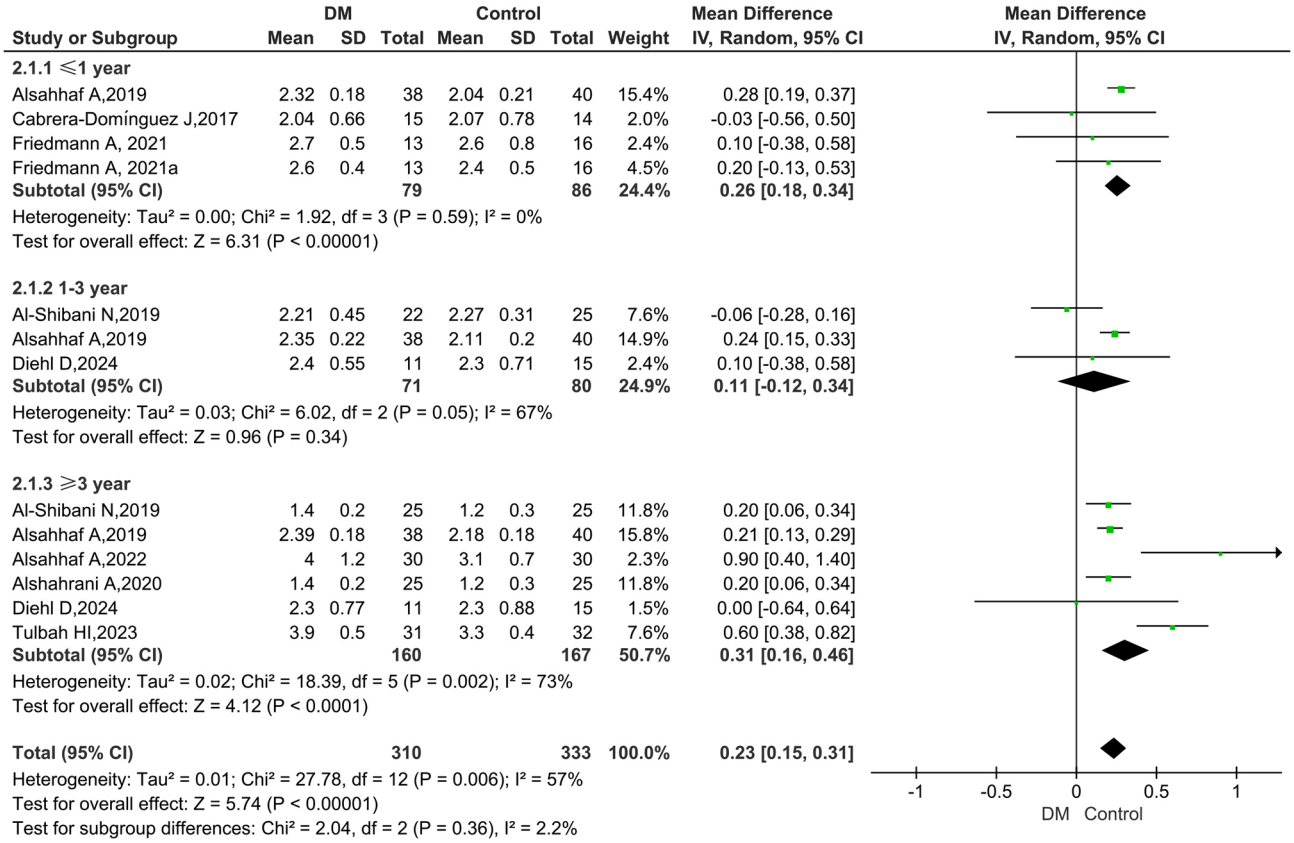

Figure 2. Forest plots of probing depth in diabetic patients compared with healthy individuals at ≤1, 1-3 and ≥3 years. DM, diabetes mellitus; SD, standard deviation; CI, confidence interval.

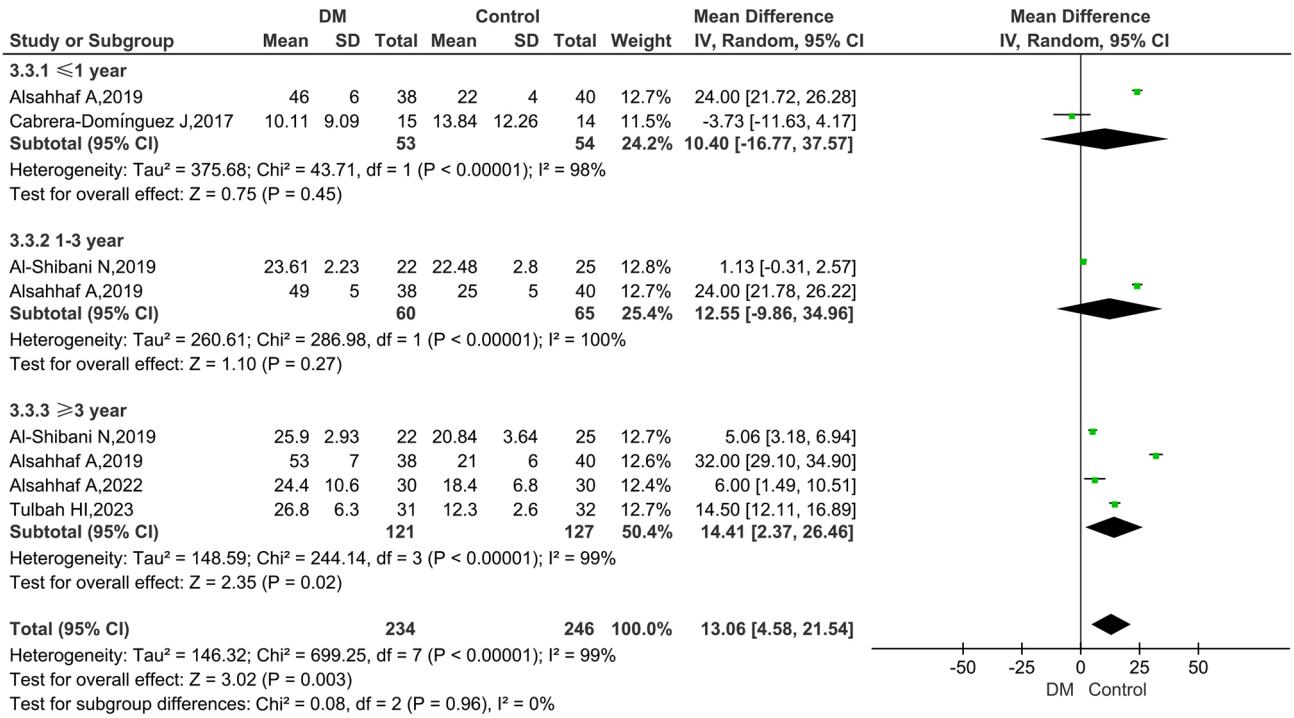

Figure 3. Forest plots of bleeding on probing in diabetic patients compared with healthy individuals at ≤1, 1-3 and ≥3 years. DM, diabetes mellitus; SD, standard deviation; CI, confidence interval.

Diabetes specifically exacerbates distal CBL around NDIs. The present study systematically evaluated the site-specific effects of diabetes on peri-implant bone levels, with key findings as follows:

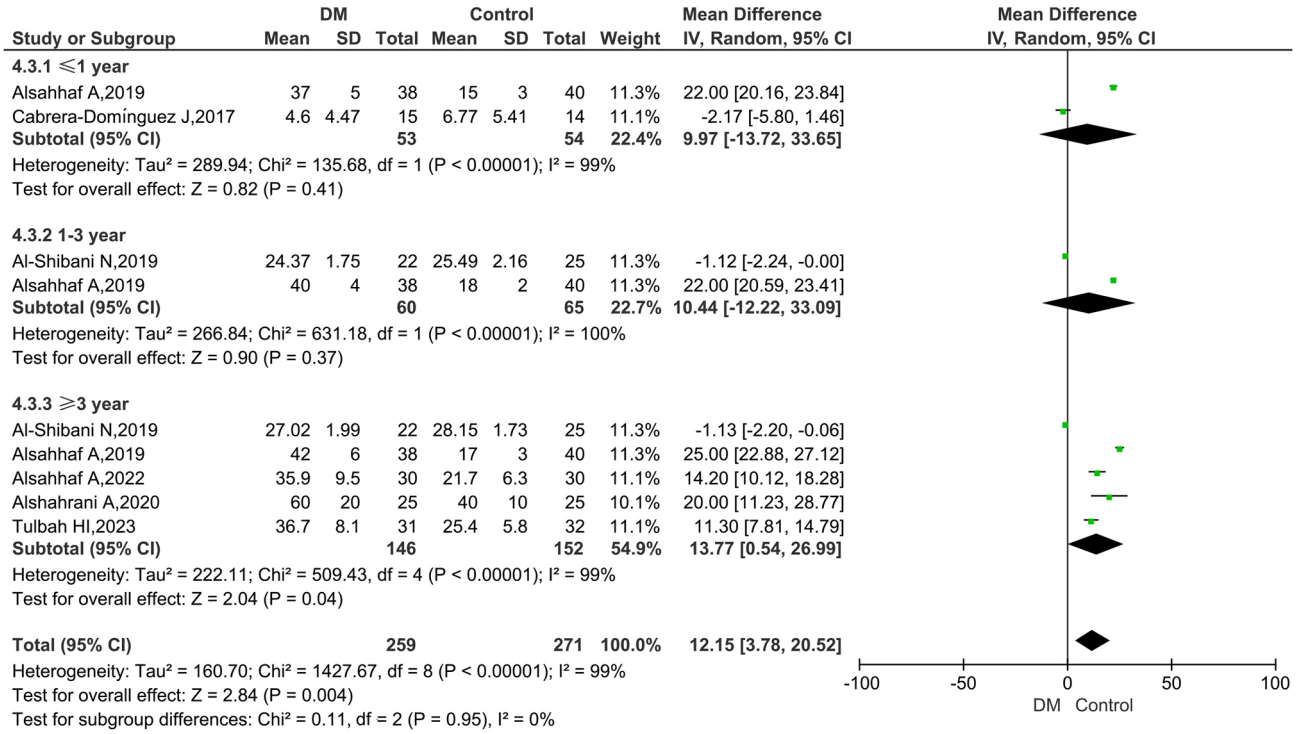

Figure 4. Forest plots of plaque index in diabetic patients compared with healthy individuals at ≤1, 1-3 and ≥3 years. DM, diabetes mellitus; SD, standard deviation; CI, confidence interval.

Mesial CBL. Pooled data from four studies (total: 217 implants) showed no significant difference in mesial CBL between groups (MD=0.31 mm; 95% CI-0.04, 0.66; P=0.08), with extreme heterogeneity (I^2=100%; random-effects model; Fig. 5A). Contradictory results primarily stemmed from Alsahhaf *et al* (14) (MD=0.80 mm; 95% CI 0.49, 1.11) and Tulbah *et al* (20) (MD=0.54 mm; 95% CI 0.51, 0.57), reporting markedly higher bone loss in patients with diabetes, contrasting with Al-Shibani *et al* (13) (pooled MD=-0.01 mm; 95% CI-0.04, 0.02), who reported no difference.

Distal CBL. Pooled data from four studies (total: 217 implants) consistently demonstrated greater distal CBL in patients with diabetes (MD=0.28 mm; 95% CI 0.02, 0.53; P=0.03). Despite high heterogeneity (I^2=97%; random-effects model; Fig. 5B), all studies showed consistent effect direction. Alsahhaf *et al* (14) (MD=0.80 mm; 95% CI 0.45, 1.15) and Tulbah *et al* (20) (MD=0.40 mm; 95% CI 0.36, 0.44) were the primary drivers. By contrast, Al-Shibani *et al* (13) (pooled MD=0.04 mm; 95% CI -0.02, 0.09) showed a positive trend despite not reaching statistical significance.

Marginal bone loss. Pooled data from four studies (total: 158 implants) revealed no intergroup differences in MBL (MD=-0.02 mm; 95% CI -0.21, 0.17; P=0.83), with perfect consistency across studies (I^2=0%; fixed-effects model; Fig. 5C). These findings suggested that distal CBL may be more susceptible to diabetes-related changes (+0.28 mm) than mesial sites, possibly reflecting the combined influence of occlusal force distribution (predominant distal loading in posterior regions) and metabolic dysregulation. However, given the extremely high heterogeneity in both distal and mesial CBL analyses, these results should be considered exploratory and cautiously interpreted. By contrast, the stable MBL confirms that diabetes does not affect initial healing with standardized procedures.

Diabetes did not affect the NDI SR. A total of four studies reported implant SRs, and these SRs were calculated at mixed follow-up durations: 6 months (17), 1 year (19), 2 years (16), and 4 years (18). Pooled analysis of these four studies (total: 112 patients) revealed consistently high implant SRs (≥95%) in patients with and without diabetes, with no significant difference between groups (RR=1.00; 95% CI 0.93, 1.07; P=1.00) and excellent consistency across studies (I^2=0%; fixed-effects model; Fig. 6). All four studies reported complete follow-up, with no dropouts or losses due to follow-up that would affect the at-risk population at the time of SR assessment.

Sensitivity analysis. The results of the leave-one-out sensitivity analysis for all outcomes demonstrated the robustness of the meta-analysis results. For PI, the overall conclusion of higher PI in patients with diabetes remained unchanged regardless of study exclusion, with consistent directional effects across follow-up subgroups and no statistically significant intersubgroup differences (P>0.05). For MBL, effect sizes showed minimal variation (-0.09-0.07 mm) upon any study exclusion, with all CIs including zero and no statistically significant individual study results (P>0.05).

Publication bias. Assessment of publication bias for PD, BOP and PI using funnel plots revealed approximate symmetrical distributions of effect sizes around the pooled estimates for all three parameters, suggesting no significant publication bias in the meta-analysis of PD, BOP, and PI outcomes (Fig. 7). However, because small number of studies included in the

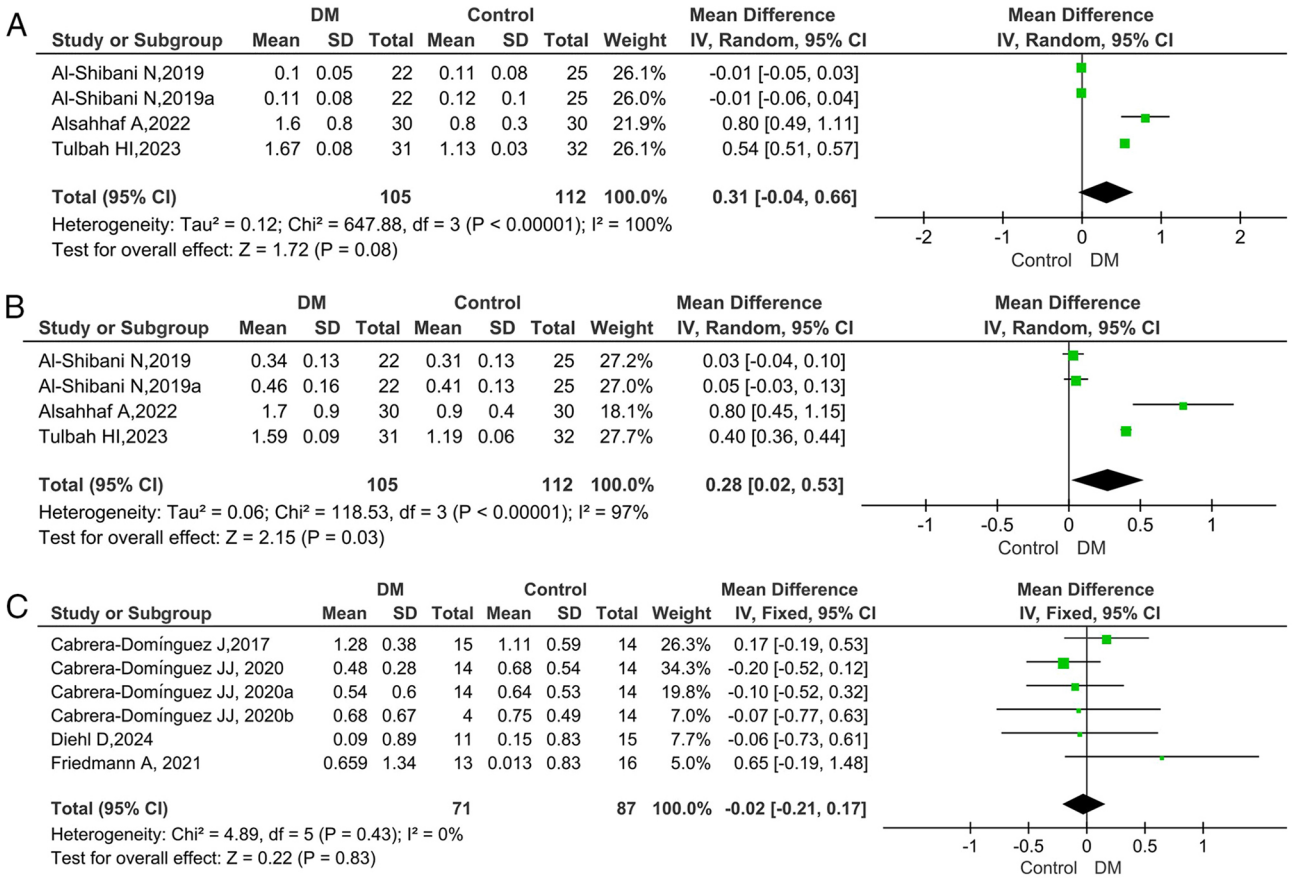

Figure 5. Forest plots of peri-implant bone levels in diabetic patients compared with healthy individuals. (A) Mesial crestal bone loss; (B) distal crestal bone loss; (C) marginal bone loss. DM, diabetes mellitus; SD, standard deviation; CI, confidence interval.

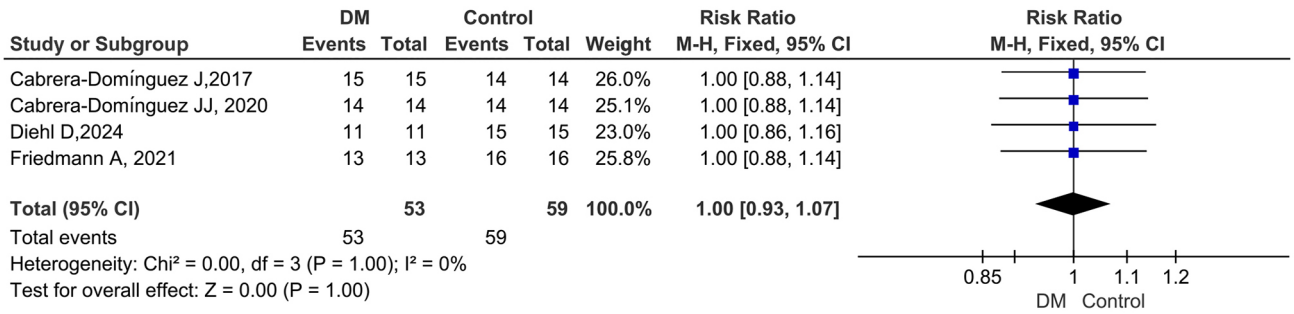

Figure 6. Forest plots of implant survival rate. DM, diabetes mellitus; SD, standard deviation; CI, confidence interval.

aforementioned indicators (<10) is small, these results should be cautiously interpreted.

Discussion

To the best of the authors' knowledge, the present study was the first systematic review and meta-analysis evaluating the efficacy of NDIs for dentition defect restoration in patients with diabetes. The comprehensive analysis revealed that while implant SR was comparable between patients with and without diabetes, individuals with diabetes exhibited more aggressive peri-implantitis manifestations during long-term follow-up, including increased PD (MD=0.31 mm), elevated BOP (MD=14.41%), and exacerbated distal bone resorption (MD=0.28 mm). These findings suggested that although NDIs achieve satisfactory short-term SRs in patients with diabetes, diabetes-associated metabolic dysregulation may impair long-term peri-implant tissue stability via multiple mechanisms. The clinical implications and potential pathological mechanisms underlying these observations, supported by current evidence, are discussed below.

In the present study, PD, a critical indicator for assessing peri-implant tissue health and detecting early complications, exhibited statistically significant time-dependent dynamic changes in patients with diabetes. The observed short-term (≤1 year) PD elevation (MD=0.26 mm) likely stems from hyperglycemia-induced vascular endothelial dysfunction and microcirculatory impairment, exacerbating postsurgical

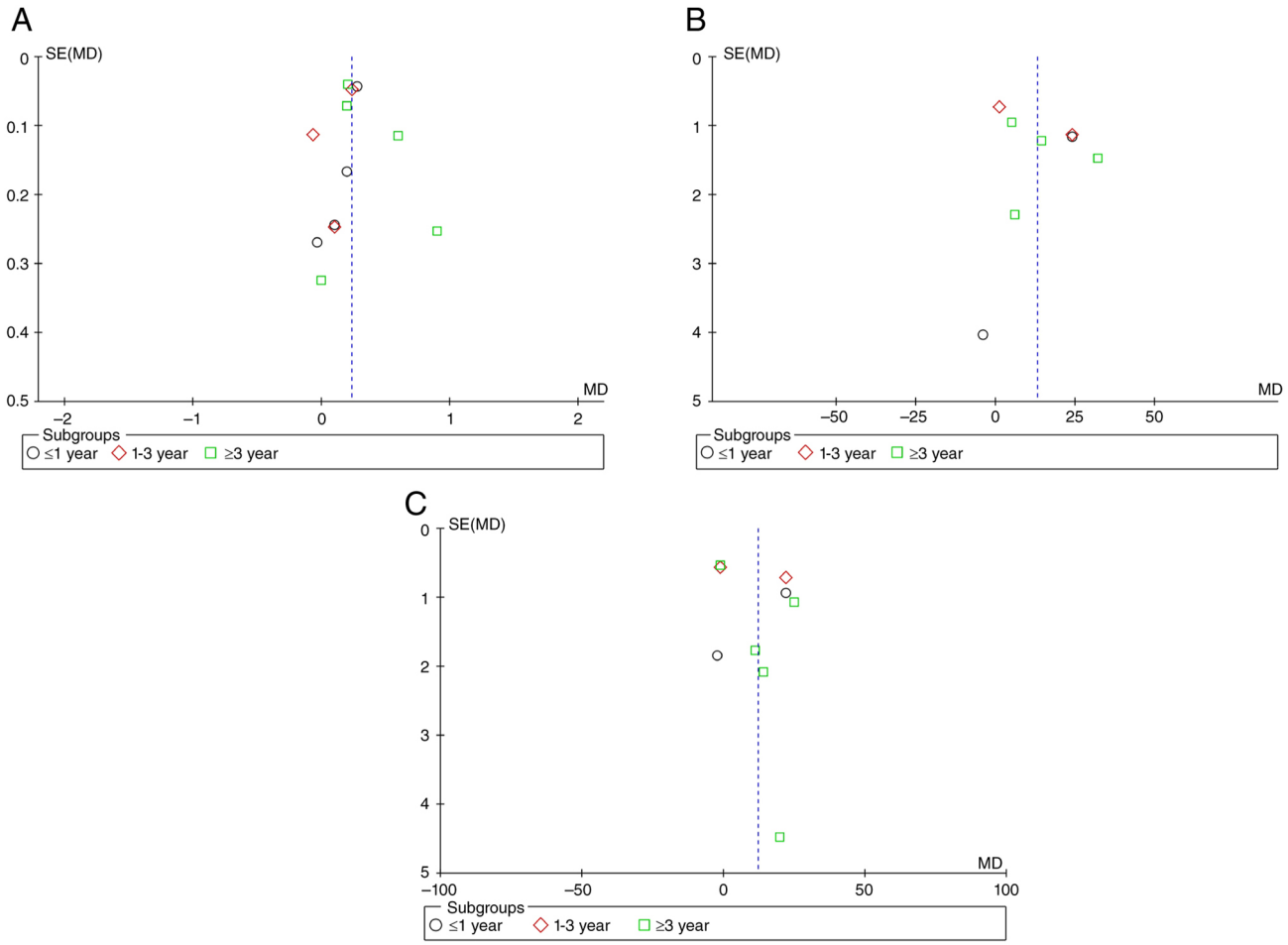

Figure 7. Funnel plots of peri-implant outcomes in diabetic patients compared with healthy individuals. (A) Probing depth; (B) bleeding on probing; (C) plaque index. SE, standard error; MD, mean difference.

ischemia-reperfusion injury and amplifying local inflammation (16). Concurrently, AGEs activate the receptor for advanced glycation end products (RAGE)-nuclear factor kappa B (NF-κB) pathway, triggering early proinflammatory cytokine release, while impaired neutrophil function suppresses vascular endothelial growth factor expression and compromised fibroblast proliferation collectively delays initial healing (21). The mid-term (1-3 years) absence of intergroup differences may be associated with improved glycemic control (such as HbA1c reduction from 7.8-7.1%) (10) and regular periodontal maintenance (professional cleaning every 6 months) (18,19), which jointly mitigate the adverse effects of hyperglycemia. Furthermore, the combination of NDIs with platform switching (15) likely contributes to the formation of thicker peri-implant mucosal tissues. Moreover, advanced implant surface treatments (such as SLActive hydrophilic surface) and modified materials (titanium-zirconium alloy) may enhance tissue remodeling and angiogenesis (17-19). However, the long-term (≥3 years) resurgence in PD values (MD=0.31 mm) results from multifactorial synergism: Chronic inflammation due to persistent AGE-RAGE axis activation, progressive bone loss driven by NF-κB receptor activator ligand/osteoprotegerin ratio imbalance and declining tissue repair capacity due to diabetic microangiopathy (22).

The presence of BOP, a sensitive indicator of peri-implant inflammatory activity, necessitates clinical attention to assess potential infection risks. The present study revealed a distinct temporal pattern of BOP in patients with diabetes. Short-term (≤1 year) and mid-term (1-3 years) follow-up showed no significant intergroup differences, which was due to the masking effects of postsurgical trauma, with nondiabetic BOP stemming from surgical injury-induced vascular responses (such as hyperplasia/exudation) and diabetic BOP reflecting hyperglycemia-aggravated microvascular dysfunction and heightened inflammation (15-17). Thus, both groups exhibited similarly high BOP levels in the early postoperative phase (14). Additionally, improved glycemic control post implantation temporarily mitigated microvascular inflammation in some patients with diabetes, delaying BOP progression (14). However, long-term (≥3 years) follow-up showed worsening diabetic BOP due to chronic hyperglycemia-induced capillary basement membrane thickening and endothelial dysfunction, increasing vascular fragility (20). Elevated levels of salivary glucose promote pathogen colonization (such as *Porphyromonas gingivalis* and *Aggregatibacter actinomycetemcomitans*) (10), exacerbating plaque-induced inflammation. Furthermore, hyperglycemia impairs fibroblast function and collagen metabolism, rendering the gingival tissues chronically fragile (16). This delayed deterioration

underscores the necessity for long-term microcirculatory monitoring and strict plaque control in patients with diabetes and dental implants.

PI, a key quantitative measure of microbial accumulation on implant surfaces, directly reflects patients' oral hygiene efficacy. The present study demonstrated a statistically significant temporal pattern in peri-implant PI among patients with diabetes. The absence of short-term (≤1 year) and mid-term (1-3 years) intergroup differences may be attributed to i) transient postoperative improvement in oral hygiene practices temporarily offsetting diabetic effects (18); ii) reduced salivary glucose exudation through intensive glycemic control, indirectly slowing plaque accumulation (14); and iii) regular professional maintenance partially balancing group differences. However, long-term (≥3 years) follow-up revealed markedly higher PI in patients with diabetes, likely due to chronic hyperglycemia-induced microangiopathy of salivary glands causing decreased saliva flow (17) and altered composition (such as elevated glucose levels), creating an optimal environment for cariogenic and periodontal pathogens, persistent neutrophil dysfunction impairing biofilm clearance (23), and progressive oral dysbiosis forming more complex, mature biofilm structures (24). This dynamic evolution suggests the need for staged plaque-control strategies in patients with diabetes and dental implants, including early-phase emphasis on intensive education and short-term glycemic control, and long-term focus on preserving salivary gland function and modulating microbial ecology.

The present study revealed distinct anatomical site-specific differences in peri-implant bone loss among patients with diabetes. Although mesial CBL was marginally higher in patients with diabetes (MD=0.31 mm), it lacked statistical significance (P=0.08), likely due to protective anatomical advantages, including thicker cortical bone and richer vascular supply that partially counteracted diabetes-induced metabolic impairments (13,25). By contrast, distal sites showed statistically markedly greater bone loss in patients with diabetes (MD=0.28 mm; P=0.03), attributable to three key factors: i) Disproportionate nonaxial occlusal loading exacerbating stress-related resorption under diabetic bone metabolism dysfunction (AGE-mediated osteoblast inhibition) (20), ii) difficult-to-clean distal anatomy combined with elevated salivary glucose levels promoting pathogen colonization and localized inflammation (10,26) and iii) delayed bone-implant interface healing amplifying micromotion-induced osteoclast activation (27). Notably, despite these regional disparities, overall MBL showed no intergroup difference (MD=-0.02 mm; P=0.81). This is likely attributable to mesial bone stability partially offsetting distal loss (14,20) and optimized implant systems (such as titanium-zirconium alloy with an SLActive surface), enhancing osseointegration resilience against diabetic effects (17-19). These findings emphasized the necessity of site-specific evaluation of peri-implant bone loss in patients with diabetes, as MBL alone may mask localized pathological changes, and highlighted the clinical imperative to prioritize distal site protection and monitoring while leveraging advanced implant designs to optimize outcomes.

Despite demonstrating statistically markedly higher PD, BOP, and PI during long-term follow-up, along with increased distal CBL (0.28 mm), both diabetic and nondiabetic groups achieved 100% NDI SRs without significant differences. This apparent paradox of worse peri-implant inflammatory parameters, yet equivalent SRs, can be ascribed to several factors. First, the absolute magnitude of the observed differences was relatively small. A 0.23-0.31 mm increase in PD and a 0.28 mm increase in distal CBL, while statistically significant, likely falls below the threshold required to compromise implant structural integrity or precipitate clinical failure within the short-to-medium-term follow-up period (≤3 years) (16-19). This is consistent with reports suggesting that short-term loss of small magnitudes of peri-implant bone is unlikely to affect implant survival (28). Second, all included studies enrolled patients with relatively well-controlled to moderately controlled diabetes, with mean HbA1c levels of 6.5-7.9% (10,13,16-20), except for one study that included a subgroup with poor glycemic control (mean HbA1c: 8.8%) (15). Glycemic control within this range has been established to mitigate diabetes-related complications and support normal wound healing and osseointegration (29). Third, optimized implant design (titanium-zirconium alloy with an SLActive hydrophilic surface) counteracts diabetes-induced bone metabolic impairments by enhancing mechanical strength and promoting early osseointegration (30). Moreover, the narrow-diameter design circumvented the need for bone augmentation procedures, minimizing surgical trauma, which is particularly advantageous for patients with delayed wound healing associated with diabetes (23). Furthermore, strict case selection criteria and standardized maintenance (professional cleaning every 3-6 months) mitigated systemic risks (14,15). Finally, the follow-up durations among studies reporting survival outcomes, predominantly short-to-medium-term survival outcomes (6 months, 1 year, and 2 years) (16,17,19), may be insufficient to reveal long-term diabetes-associated complications, with only one study providing follow-up data at 4 years (18). Collectively, these findings suggest that NDIs remain mechanically stable, with comparable SRs in patients with well-controlled diabetes within the short-to-medium term. However, diabetes is associated with a modestly worse peri-implant inflammatory profile and localized distal bone changes (14), which may warrant closer monitoring, particularly beyond 3 years of function. Further studies with extended follow-ups are warranted to determine whether these small but statistically significant differences ultimately translate into clinically meaningful increases in implant failure or peri-implantitis risk over the long term, particularly among patients with suboptimal glycemic control or oral hygiene (31).

In the present meta-analysis, the three outcomes of PD, BOP, and mesial CBL around NDIs showed substantial heterogeneity between diabetic and nondiabetic populations. Numerous factors may contribute to this variability. First, differences in implant systems represent an important contributing factor. Some studies used titanium-zirconium (Ti-Zr) alloy implants with hydrophilic surfaces (16-19), which possess superior mechanical properties and osseointegration capacity compared with conventional pure Ti implants (10,13). Furthermore, some studies used platform-switching designs, which may reduce MBL through favorable stress distribution (15,20). Among the nine included studies, four used Ti-Zr alloy implants with hydrophilic surfaces (16-19), while the remaining five used conventional

Ti implants with moderately rough surfaces (10,13,15,20). However, in this meta-analysis, no clear pattern emerged regarding effect size differences between these two implant types across the outcomes analyzed, possibly due to confounding by other factors such as follow-up duration and glycemic control levels. Second, variations in measurement methods and outcome parameter definitions existed across studies, including differences in the number of measurement sites for PD and BOP (such as four-site vs. six-site protocols), periodontal probe types (UNC-15 vs. PCP-11) and reference points for bone loss assessment (implant shoulder, platform margin, or the starting point of osseointegration) (10,14,20). Such measurement heterogeneity directly influenced the pooled analyses. Third, there were considerable differences in patients' glycemic control levels and diabetes duration across the studies. Although most adopted HbA1c >6.5% as the inclusion criterion for diabetes (10,13-15), the mean HbA1c in some diabetic groups was ~7.0% (18,19) and others exceeded 8.0% (16,20). Poor glycemic control is closely associated with aggravated peri-implant inflammatory responses and increased bone resorption (32). Moreover, diabetes duration varied substantially across studies, with an approximate threefold difference [shortest mean duration: 3.7 years (15) and longest mean duration: 11.3 years (10)]. Such disparities in diabetes duration influence cumulative damage to immune status and bone metabolism (33). Fourth, among the included studies, five were prospective cohort studies (13,16-19) and four were retrospective cohort or cross-sectional studies (10,14,15,20). Prospective studies generally have lower risk of bias due to prespecified protocols and standardized data collection. In this meta-analysis, prospective studies tended to report smaller effect sizes for PD and CBL compared with retrospective studies, suggesting that retrospective designs may overestimate differences between diabetic and non-diabetic patients, potentially contributing to the high heterogeneity observed. Finally, differences in study design and implant placement location cannot be ignored. Regarding study design, all nine included studies employed a parallel-group design, comparing independent cohorts of diabetic and non-diabetic patients. While this design avoids the carry-over effects associated with split-mouth designs, it is more susceptible to confounding due to inter-individual variability in baseline characteristics (such as oral hygiene habits and glycemic control status), which may have increased statistical heterogeneity. Regarding implant placement location, some studies exclusively included posterior regions (10,13,19), whereas others involved anterior sites or mixed locations (18-20). Posterior regions are characterized by higher bone density (particularly in the mandible), greater occlusal forces, and less stringent esthetic requirements compared with anterior regions. These anatomical and functional differences may affect PD and CBL measurements (34). Notably, studies focusing on posterior sites (10,13,19) tended to report higher PD and CBL values compared with those including anterior sites, suggesting that implant location may contribute to the observed heterogeneity. Therefore, the findings of the present meta-analysis should be cautiously interpreted.

The present study had several limitations that must be acknowledged. First, a key limitation is the inability to perform subgroup analyses based on glycemic control (such as HbA1c ≤7 vs. >7%) due to insufficient data in the included studies. Glycemic control is recognized as a critical factor influencing implant outcomes in patients with diabetes. However, the primary studies either did not report outcomes stratified by HbA1c levels or provided insufficient detail to enable such subgroup comparisons. Second, the predominance of short-term follow-up data (≤5 years) may underestimate long-term diabetes-associated complications. Given the chronic nature of diabetes-related metabolic impairments, longer-term data (≥7 years) are necessary to validate the sustainability of NDI efficacy. Third, the relatively small sample sizes in the subgroup analyses limited statistical power and may have increased the risk of biased estimates. Fourth, significant heterogeneity was observed across key outcomes (I^2: 57-100%), which likely stemmed from differences in implant surface characteristics (such as hydrophilic vs. moderately rough surfaces), surgical protocols (such as flap design and implant placement depth), and postoperative maintenance schedules. The inconsistent reporting of these details hindered the ability to adjust for potential confounders that may influence peri-implant outcomes. Fifth, this meta-analysis represents a pooled snapshot of SRs at various follow-up time points rather than a time-to-event analysis. Sixth, the potential effect of diabetes-related comorbidities (such as cardiovascular disease and nephropathy) on NDI outcomes could not be assessed because most included studies either excluded patients with significant comorbidities or did not report this information. These conditions may independently affect peri-implant healing and bone metabolism, and their role in modifying implant outcomes in patients with diabetes remains unelucidated. Seventh, the present meta-analysis focused on objective clinical and radiographic parameters (such as MBL and PD), as these were the most consistently reported outcomes across the included studies. Patient-reported outcomes (PROs), such as implant stability, masticatory function, aesthetic satisfaction and quality of life, are valuable for comprehensive assessing the clinical utility of NDIs in diabetic patients' daily lives. However, these PROs could not be evaluated due to insufficient data in the included studies. Eighth, the absence of a formal GRADE assessment limits the certainty appraisal of the pooled findings. Finally, the absence of direct comparisons between narrow- and standard-diameter implants restricts clinical guidance on diameter selection. Future large-scale, long-term prospective studies with standardized glycemic stratification, outcome assessment protocols, and PRO measures (such as masticatory function, aesthetic satisfaction and quality of life) are necessary to provide more robust evidence and to further elucidate the long-term efficacy of NDIs in patients with diabetes.

Based on current evidence, the present meta-analysis demonstrated that NDIs achieve comparable short-term SRs in patients with well-controlled diabetes. However, long-term outcomes pose significant challenges because diabetes specifically exacerbates peri-implant inflammation (manifested as a 0.31 mm increase in PD and a 14.41% higher BOP) and distal bone resorption (0.28 mm), with these disparities widening over time. These findings underscore the need for strict glycemic control, enhanced long-term monitoring (particularly of distal bone levels), and personalized maintenance protocols in patients with diabetes who receive NDIs.

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Authors' contributions

ZZ, DW and JL collaboratively completed this paper. JL took charge of the overall logical framework and meticulously reviewed the details of this work. Data authentication is not applicable. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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