Journal of Dentistry 161 (2025) 105949

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Review article

Accuracy of near-infrared reflection in detecting proximal caries: a systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Dental caries
Caries detection
Diagnosis
Near-infrared reflection
Digital dentistry

ABSTRACT

Objective: This systematic review and meta-analysis aimed to evaluate the accuracy of near-infrared reflection (NIRR) technology in detecting proximal dental caries compared to the reference standard.
Data: This review followed PRISMA guidelines and was registered in PROSPERO (CRD42024570850). The pooled sensitivity, specificity, and the area under the summary receiver operating characteristic curve (AUC) of NIRR were calculated from the accuracy parameters extracted from the included studies. The quality of the studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) tool.
Sources: Publications from PubMed, MEDLINE, Scopus, and Web of Science.
Study selection/results: Thirteen studies, including six *in vitro* and seven clinical studies, met the eligibility criteria. Most of the included studies assess NIRR employing near-infrared light with a wavelength of 850 nm, while 780, 1050, 1550, and 1600 nm NIR were adopted in a few studies. The pooled data from *in vitro* studies revealed that the sensitivity (95 % Confidence Interval, CI), specificity (95 % CI) and AUC of NIRR for proximal caries detection were 0.46(0.42–0.50) and 0.87(0.84–0.89), and 0.72, respectively. For clinical studies, the pooled sensitivity (95 % CI), specificity (95 % CI), and AUC were 0.65(0.62–0.68), 0.95(0.94–0.95) and 0.83, respectively. Seven studies showed a low risk, five studies showed a high risk, and one study showed an unclear risk of bias and applicability concerns.
Conclusion: NIRR is relatively insensitive but highly specific for the detection of proximal dental caries in posterior teeth. Due to the heterogeneity of the included studies, a cautious interpretation of the results is necessary. Future research is needed to confirm the potential of NIRR in detecting dental caries, particularly NIRR that utilizes longer wavelengths.
Clinical significance: NIRR is a novel technology for caries detection. This study provides valuable information to researchers and clinicians who are interested in using this technology for caries detection.

1. Introduction

Dental caries remains a significant global health issue, with approximately 2 billion adults and 514 million children suffering from this condition [1]. As a progressive disease, undiagnosed or untreated caries can induce pain, cause infections, lead to tooth loss, and in severe circumstances, instigate broader health complications. Because dental caries can be reversed at its early stage [2,3], early identification of caries facilitates prompt intervention, thus impeding further disease progression. Detecting and diagnosing dental caries at its early stage is key to managing dental caries with the most suitable treatment approach, ranging from non-restorative strategies [4] and minimally invasive treatments [5], which allows for preserving dental hard tissue and extending the lifespan of nature teeth. This highlights the importance of accurate approaches for early detection and assessment of dental caries [6].

Detecting and diagnosing dental caries could be challenging, particularly those on proximal surfaces of the tooth [7]. The conventional clinical detection of dental caries normally includes visual-tactile examination combined with bitewing radiographic examination [8].

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https://doi.org/10.1016/j.jdent.2025.105949
Received 10 April 2025; Received in revised form 28 June 2025; Accepted 1 July 2025
Available online 3 July 2025

Table 1
The keywords of electronic search in various databases.

Database	Keywords
PubMed & MEDLINE	("Caries" OR "Tooth Decay" OR "Dental Caries[MeSH]") AND ("Near-infrared light reflection" OR "NIR" OR "Near-Infrared" OR "Near-infrared" OR "Near-IR imaging" OR "Near-Infrared Spectroscopy")
Scopus & Web of Science	(("Caries" OR "Tooth Decay" OR "Dental Caries") AND ("Near-infrared light reflection" OR "NIR" OR "Near-Infrared" OR "Near-infrared" OR "Near-IR imaging" OR "Near-Infrared Spectroscopy"))

Proximal caries manifest on the surfaces of teeth that are adjacent to each other, which makes visual or tactile inspection difficult, if not impossible [9]. Bitewing radiographs are not sensitive and may fail to identify proximal caries in their early stages [8,10–15]. Due to the high prevalence of proximal caries in adolescents and adults and the cruciality of detecting them [16,17], there is a rising research trend on the advancement of digital diagnostic aids for proximal caries detection, particularly light-based instruments [7,18].

Near-infrared technology has been adopted in digital devices for dental caries detection. It offers a non-invasive, radiation-free approach that enhances patient comfort and safety [19]. This technology leverages a specific range of wavelengths to identify the changes in tooth structure [20,21]. Caries detection devices with near-infrared technology normally work by employing the near-infrared transillumination (NIRT) or near-infrared reflection (NIRR) method [21,22]. NIRT operates on the principle of light transmission, while NIRR is based on light

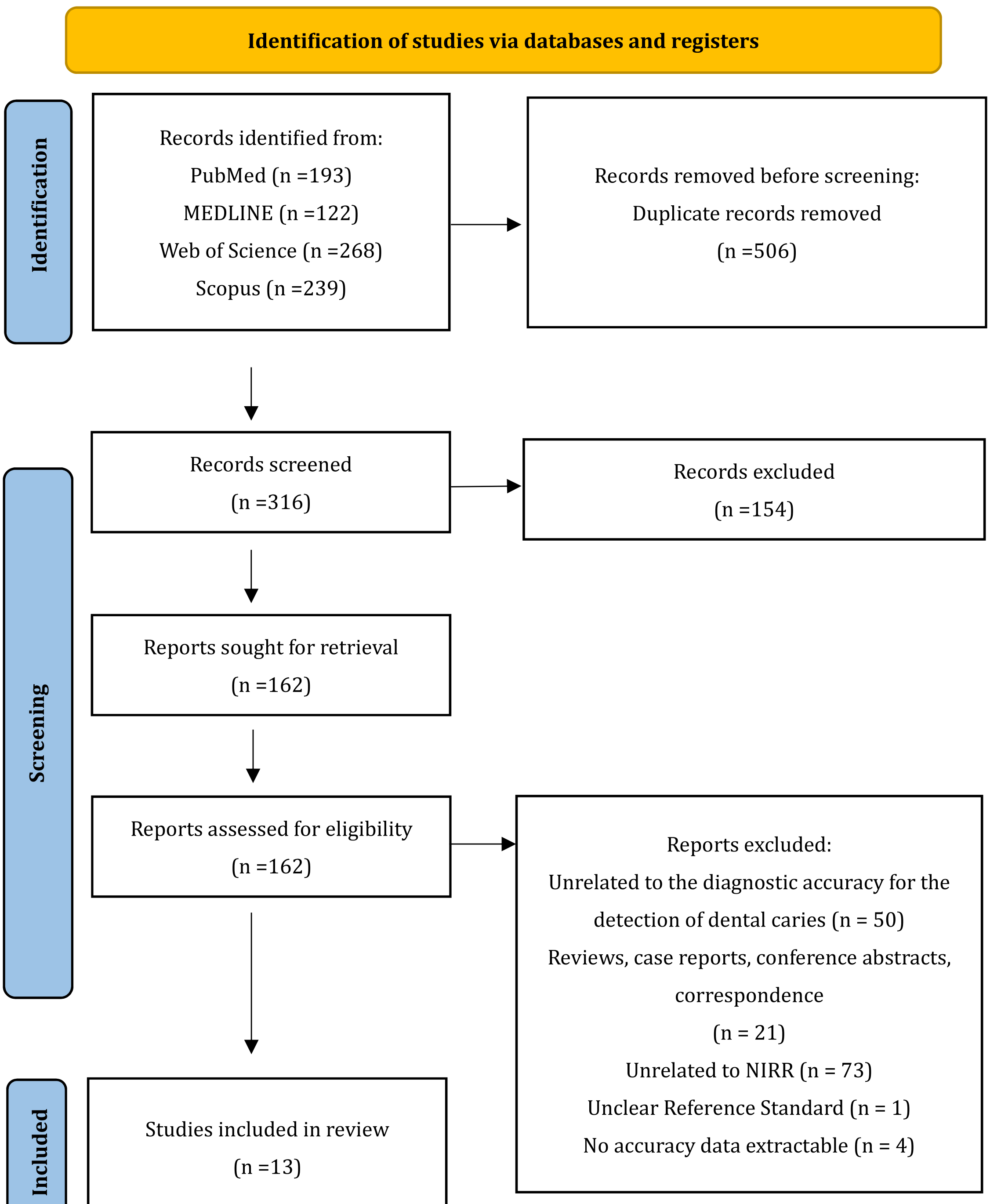

Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram illustrating the search process of the study.

Table 2
Characteristics of the included studies, categorized into *in vitro* and clinical studies, ordered by wavelength and publication year.

Study	Country	Setting	Wave-Length (nm)	Device	Dentition	Location	Sample Size (surfaces, teeth, patients)	Reference test	Sensitivity	Specificity
Heck et al. 2021	Germany	*in vitro*	780	Non-commercial	permanent	molars and premolars	250, 250, NA	µCT	0.29	0.84
Lederer et al. 2019	Germany	*in vitro*	850	Vistacam IX Proxi	permanent	molars and premolars	100, NA, NA	µCT	0.50	0.98
Litzenburger et al. 2022	Germany	*in vitro*	850	i-Tero	permanent	molars and premolars	250, NA, NA	µCT	0.33	0.84
Hoxie et al. 2024	USA	*in vitro*	850	i-Tero	NA	molars and premolars	98, NA, NA	µCT	0.53	0.89
Oliveira et al. 2024	Brazil	*in vitro*	850	i-Tero	primary	molars	182, NA, NA	Histological Examination	0.44	0.95
Heck et al. 2024	Germany	*in vitro*	1050 1550	Non-commercial	permanent	molars and premolars	250, 250, NA	µCT	0.44 0.73	0.96 0.76
Ahrari et al. 2021	Iran	clinical	850	Vistacam IX Proxi	permanent	molars and premolars	43, NA, 15	Visual and tactile	0.89	0.15
Metzger et al. 2022	Germany	clinical	850	i-Tero	permanent	molars and premolars	3426, NA, 100	BWR	0.73	0.97
Cao et al. 2023	China	clinical	850	i-Tero	primary	molars	871, NA, 126	BWR	0.74	0.91
Cuenin et al. 2024	USA	clinical	850	i-Tero	permanent and primary	molars and premolars	344 (283 permanent, 61 primary), NA, 17	BWR	0.23	0.96
Kanar et al. 2024	Turkey	clinical	850	i-Tero	permanent	molars and premolars	639, NA, 22	BWR	0.52	0.94
Simon et al. 2016	USA	clinical	1600	Non-commercial	permanent	premolars	109, 109, 40	PLM, and TMR	0.27	0.92
Zhu et al. 2023	USA	clinical	1600	Non-commercial	permanent	premolars	240, 135, 40	PLM and µCT	0.72	0.86

Abbreviations: BWR, Bitewing Radiographs; µCT, micro-computed tomography; NA, Not Available; PLM, Polarized Light Microscopy; TMR, Transverse Microradiography.

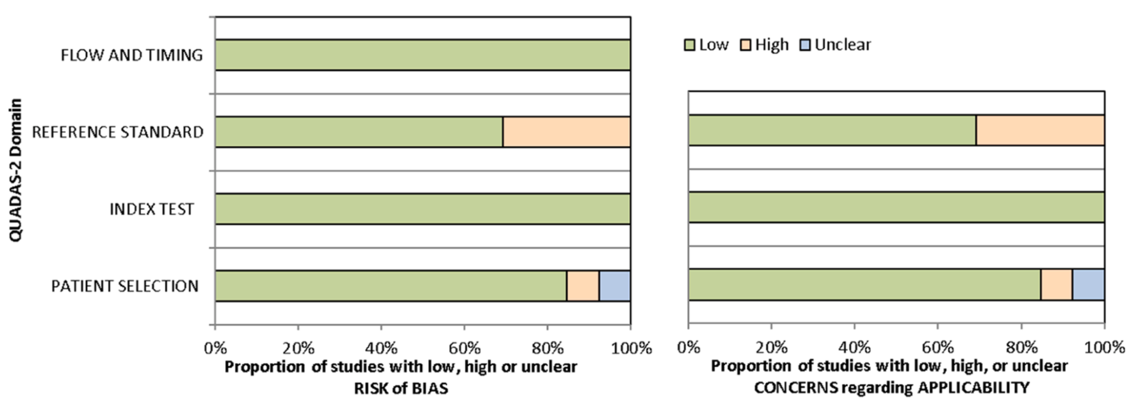

Fig. 2. Summary of QUADAS-2 risk of bias and applicability concern assessment. The proportion of included studies with low, unclear, or high risk of bias or applicability concerns in each domain is shown (%).

Table 3
Results of meta-analysis.

	Study No. (publications)	Total tooth surfaces	Sensitivity (95 % CI)	Heterogeneity I-square	Specificity (95 % CI)	Heterogeneity I-square	SROC AUC (SE)	Q* (SE)
in vitro studies	7(6)	1379	0.46 (0.42–0.50)	87.3 %	0.87 (0.84–0.89)	86.4 %	0.72(0.13)	0.66(0.11)
clinical studies	7(7)	5702	0.65 (0.62–0.68)	92.9 %	0.95 (0.94–0.95)	97.1 %	0.83(0.07)	0.76(0.06)

Abbreviations: AUC, Area Under the Curve; CI, confidence interval; Q*, the point of the curve in which sensitivity equals specificity; SE, standard error; sROC, Summary receiver operating characteristics;.

reflection. At near-infrared wavelengths, dental enamel becomes highly transparent, significantly improving the contrast between sound enamel and demineralized (carious) enamel, thereby facilitating the differentiation and identification of carious areas [22].

The utilization of NIRR in caries detection has been witnessing a remarkable increase in the past decade. The key driver of this trend could be the operational advantages offered by NIRR. Unlike NIRT, NIRR does not necessitate the use of two arms clamping the teeth to emit near-infrared light from the device's detecting head, thereby simplifying the detection procedure. These properties make NIRR ideal for use in

Table 4
QUADAS-2 risk of bias and applicability concerns of included studies.

Study	RISK OF BIAS				APPLICABILITY CONCERNS		
	PATIENT SELECTION	INDEX TEST	REFERENCE STANDARD	FLOW AND TIMING	PATIENT SELECTION	INDEX TEST	REFERENCE STANDARD
Ahrari et al. 2021	☹	☺	☺	☺	☹	☺	☺
Cao et al. 2023	☺	☺	☹	☺	☺	☺	☹
Cuenin et al. 2024	☺	☺	☹	☺	☺	☺	☹
Heck et al. 2021	☺	☺	☺	☺	☺	☺	☺
Heck et al. 2024	☺	☺	☺	☺	☺	☺	☺
Hoxie et al. 2024	?	☺	☺	☺	?	☺	☺
Kanar et al. 2024	☺	☺	☹	☺	☺	☺	☹
Lederer et al. 2019	☺	☺	☺	☺	☺	☺	☺
Litzenburger et al. 2022	☺	☺	☺	☺	☺	☺	☺
Metzger et al. 2022	☺	☺	☹	☺	☺	☺	☹
Oliveira et al. 2024	☺	☺	☺	☺	☺	☺	☺
Simon et al. 2016	☺	☺	☺	☺	☺	☺	☺
Zhu et al. 2023	☺	☺	☺	☺	☺	☺	☺

☺Low Risk ☹High Risk ? Unclear Risk

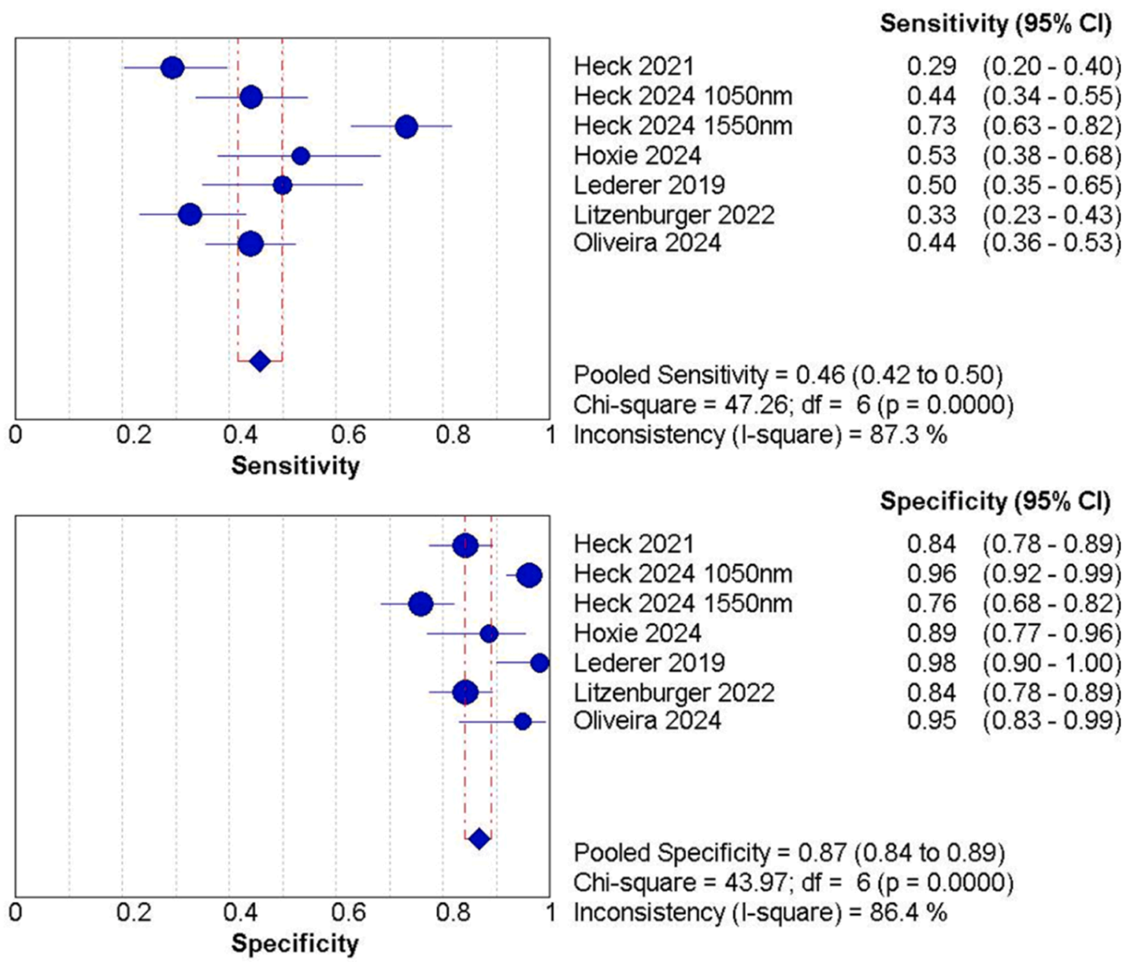

Fig. 3. Forest plot of sensitivity (3a) and specificity (3b) demonstrating the diagnostic performance of near-infrared reflection technology in detecting proximal dental caries *in vitro* studies. For each study, the plot shows study sensitivity or specificity (circle), pooled sensitivity or specificity (diamond), and 95 % confidence interval (line). Abbreviations: CI, confidence interval; df, degrees of freedom.

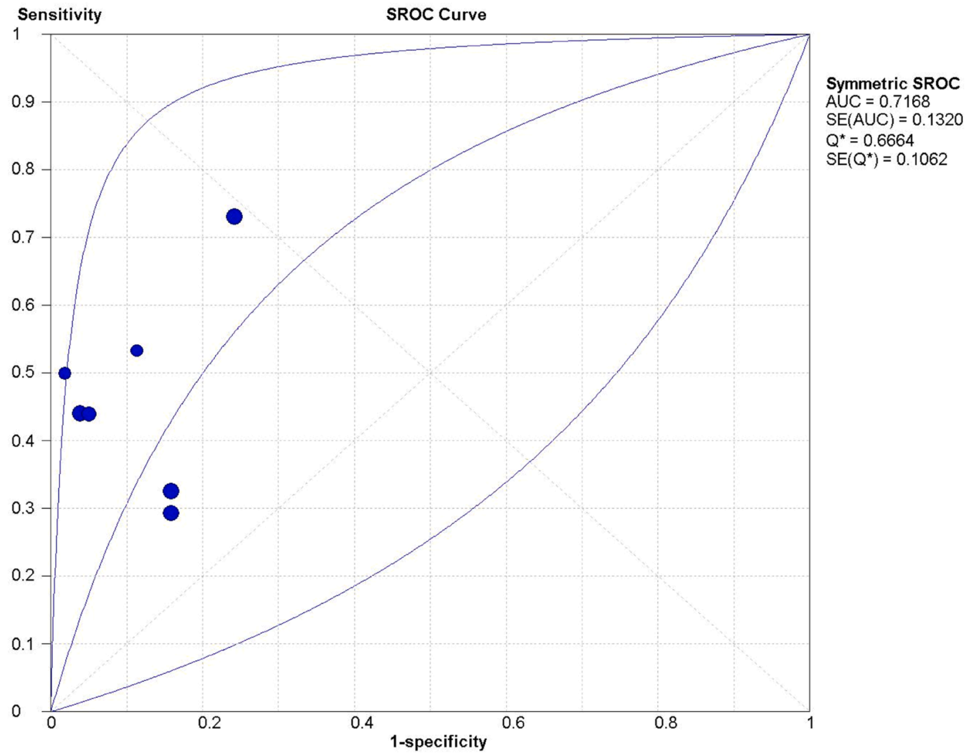

Fig. 4. Symmetric receiver operator characteristic curve and area under curve for all *in vitro* studies included in the systematic review of near-infrared reflection technology in detecting proximal dental caries. Abbreviations: SROC, symmetric receiver operator characteristic; AUC, area under curve; SE, standard error; Q*, the point of the curve in which sensitivity equals specificity.

intraoral scanners or home-use devices, enabling dental professionals and patients to identify and address dental caries at an early stage, thus improving oral health outcomes[23,24].

A recent systematic review evaluated the efficiency of near-infrared technology in detecting carious lesions [25]. However, this review did not specifically address the use of NIRR in detecting proximal caries. To our knowledge, there has been no review or meta-analysis that has explored the accuracy of NIRR technology in identifying proximal caries. Therefore, this systematic review and meta-analysis intend to scrutinize the accuracy of NIRR technology in detecting proximal caries.

2. Materials and methods

2.1. Protocol and registration

This review is reported following the international Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [26] and was registered on the PROSPERO platform with the registration code CRD42024570850.

The research question addressed in this review is: " What is the accuracy of Near-Infrared Reflection (NIRR) technology in detecting proximal dental caries compared to the reference standard?" This question was framed using the PICO strategy as follows:

(P) Population of interest: Proximal dental caries

(I) Investigated test: NIRR technology

(C) Comparator test: Reference standard including micro-computed tomography(μCT), histological examination, visual and tactile assessment, bitewing radiography(BWR), polarized light microscopy(PLM), and transverse microradiography(TMR).

(O) Outcome: Diagnostic accuracy parameters, including sensitivity, specificity, and the area under the summary receiver operating characteristic curve

2.2. Search strategy

To identify publications meeting the inclusion criteria, four electronic databases were searched: PubMed, MEDLINE, Scopus, and Web of Science. The search was performed on September 30, 2024, and was updated on January 15, 2025. Each database was searched using specific keywords as listed in Table 1. To ensure comprehensive coverage, supplementary searches were also performed on Google Scholar, and reference lists from selected studies were examined to identify any potentially overlooked publications.

2.3. Eligibility criteria

The studies selected for inclusion were required to meet the following criteria:

1. Studies involving human proximal dental caries of posterior teeth in both *in vitro* and clinical settings.
2. Studies that used NIRR technology.
3. The caries status of the examined surface must have been evaluated using a reference standard.
4. Studies that provided accuracy measures for the threshold of detecting proximal caries, with reported data that allowed for the construction of a 2 × 2 diagnostic table (True Positive, False Negative, False Positive, and True Negative).
5. Studies of any language and publication date were considered.

The exclusion criteria were as follows:

1. Studies not involving human dental caries.
2. Studies that used diagnostic methods other than NIRR technology (*e.g.*, fluorescence, artificial intelligence, NIRT).
3. Studies that used NIRR technology as the reference standard.

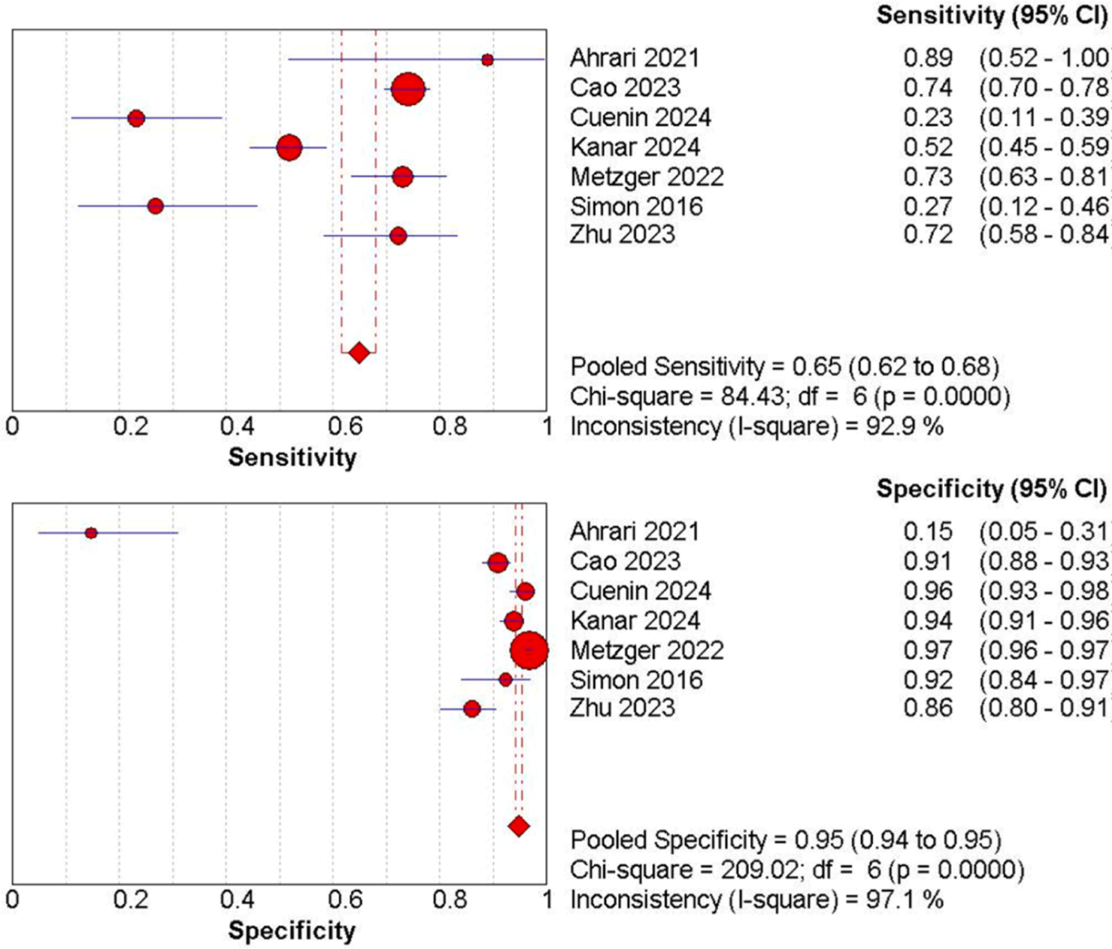

Fig. 5. Forest plot of sensitivity (5a) and specificity (5b) demonstrating the diagnostic performance of near-infrared reflection technology in detecting proximal dental caries in clinical studies. For each study, the plot shows study sensitivity or specificity (circle), pooled sensitivity or specificity (diamond), and 95 % confidence interval (line). Abbreviations: CI, confidence interval; df, degrees of freedom.

4. Studies that lacked complete metric reporting, preventing the construction of a 2 × 2 diagnostic table, were first addressed by contacting the authors via email to obtain missing information. If no data was provided, the study was excluded. However, if the data becomes available later, the study will be reassessed to determine its eligibility for inclusion.
5. Reviews, case reports, conference abstracts, correspondence, protocols, and inaccessible studies.

2.4. Study selection

The screening process was conducted in two stages independently by two assessors (KM, JCKK). The titles and abstracts are screened followed by full-text reading of the selected studies. Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia) was used to manage the data. Duplicate studies were removed both within and across databases. Full texts of potentially relevant articles were retrieved and assessed for inclusion based on the set eligibility criteria. In case of disagreements, these were discussed and resolved by consulting with the third and fourth reviewers (WYHL, OYY).

2.5. Data extraction

For studies that met the eligibility criteria, the following information was extracted using a pre-designed data extraction form: title, authors' names, publication year, study location, NIRR image acquisition device, NIRR wavelength, sample size (number of surfaces, teeth, and patients), type of teeth, diagnostic reference standard, diagnostic threshold, disease prevalence, and accuracy measures including sensitivity, specificity, true positives, false negatives, false positives, and true negatives. This data extraction process was conducted by an assessor (KM). The extracted data was then revised by a second assessor (JCKK), and later verified by third and fourth reviewers (WYHL, OYY).

2.6. Risk of bias and applicability

Two assessors (KM, JCKK) independently assessed study quality using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) criteria [27], compared results, and resolved discrepancies through discussion. If disagreements persisted, a third reviewer (OYY) provided the final decision. The QUADAS-2 evaluates four domains: patient selection, index test, reference standard, and flow and timing. Each domain was rated as low risk, high risk, or unclear risk of bias according to pre-defined criteria.

2.7. Meta-analysis

Sensitivity and specificity were pooled using a random-effects model, due to anticipated heterogeneity in sample sizes, clinical characteristics, and methodological approaches across the included studies [25,28]. To assess the interaction between sensitivity and specificity, the summary receiver operating characteristic (SROC) curves were constructed and

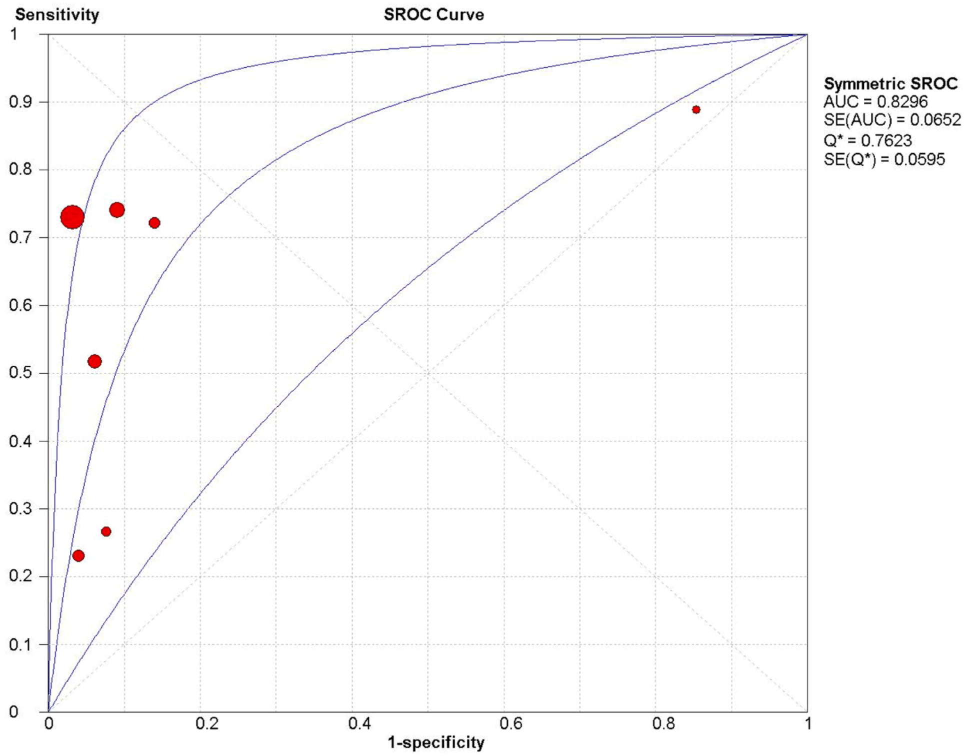

Fig. 6. Symmetric receiver operator characteristic curve and area under curve for all clinical studies included in the systematic review of near-infrared reflection technology in detecting proximal dental caries.
Abbreviations: SROC, symmetric receiver operator characteristic; AUC, area under curve; SE, standard error; Q*, the point of the curve in which sensitivity equals specificity.

the area under the SROC curve (AUC) was calculated [29]. All statistics were computed with a 95 % confidence interval (CI). Heterogeneity was analyzed using a chi-squared test and assessed with the I-squared index. All statistical analyses were carried out using MetaDiSc 1.4 software (Clinical Biostatistics Unit, Ramón y Cajal Hospital, Madrid, Spain)

3. Results

3.1. Study selection

The search strategy is summarized in the PRISMA flowchart shown in Fig. 1. The systematic search found 294 unique records. After screening titles and abstracts, 132 records were excluded. From the remaining 162 records, 149 were further excluded after full-text review. No additional studies were included after manually screening the reference lists and searching Google Scholar. Data was extracted from a total of 13 studies for the final analysis [21,30–40].

3.2. Study characteristics

Table 2 presents the characteristics of the 13 studies included in this review, six of which were *in vitro* studies [30,34,35,37,39,41] while seven were clinical studies [21,31–33,36,38,40]. These studies were published between 2016 and 2024. They were conducted in various countries including Germany (five studies) [30,34,37–39], the USA (four studies) [21,33,35,40], China (one study) [32], Iran (one study) [31], Brazil (one study) [41], and Turkey (one study) [36]. The sample sizes in these studies differed significantly. For *in vitro* studies, the sample size ranged from 98 to 250 tooth surfaces, while for clinical studies, the sample size ranged from 43 to 3426, with three studies involving >500 tooth surfaces [32,36,38]. Disease prevalence varied across studies. For *in vitro* studies, caries prevalence ranged from 0.23 to 0.46 [30,34,35,37,39,41], while for clinical studies, caries prevalence ranged from 0.03 to 0.48 [21,31–33,36,38,40].

For the *in vitro* studies, two studies assessed non-commercial NIRR devices with wavelengths ranging from 780 nm to 1550 nm [30,34]. Three studies assessed the i-Tero device (Align Technology, Santa Clara, USA), which employs NIRR of 850 nm wavelength [35,39,41]. One study assessed the Vistacam (Dürr Dental, Bietigheim-Bissingen, Germany), which also uses an 850 nm NIRR [37]. Regarding clinical studies, two studies used a non-commercial NIRR device with a wavelength of 1600 nm [21,40], four utilized the i-Tero device with an 850 nm wavelength [32,33,36,38], and one employed the Vistacam with an 850 nm wavelength [31].

In terms of tooth types examined, *in vitro* studies largely focused on permanent teeth, as assessed in four studies [30,34,37,39], one study targeted primary teeth [41], while one study did not specify the type of teeth [35]. In the case of clinical studies, five focused on permanent dentition [21,31,36,38,40], one study included both primary and permanent dentition[33], and one study targeted primary dentition [32].

For reference standards, five *in vitro* studies employed μCT [30,34,35,37,39], and one study relied on histological examination [41]. For clinical studies, four used BWR [32,33,36,38], and one used Orthodontic separators followed by visual and tactile examination [31]. One study used both PLM and μCT [40], and one used PLM, and TMR [21].

3.3. Risk of bias and applicability

For the risk of bias, seven studies were rated low across all four domains of QUADAS-2 [21,29,33,36,38–40]. One study showed unclear risk in one domain [34], while five studies showed high risk in one domain [30–32,35,37]. In terms of applicability concerns, seven studies were rated as low concern in all three domains [21,29,33,36,38–40]. Similarly, one study had unclear risk in one domain [34], while five studies had high risk in one domain [30–32,35,37]. Fig. 2 and Table 4 provide details on the risk of bias and applicability concerns.

3.4. Meta-analysis

The results of the meta-analysis are summarized in Table 3. For the *in vitro* studies, a total of 1379 tooth surfaces were included in the analysis. The pooled sensitivity was 0.46 (95 % CI: 0.42 to 0.50; p = 0.000; I-square = 87.3 %), while the pooled specificity was 0.87 (95 % CI: 0.84 to 0.89; p = 0.000; I-square = 86.4 %). The sensitivity and specificity of the six included *in vitro* studies are summarized in forest plots (Fig. 3a and b). The AUC of the SROC curve was 0.72, as shown in Fig. 4.

In the clinical studies, a total of 5702 tooth surfaces were included in the analysis. The pooled sensitivity was 0.65 (95 % CI: 0.62 to 0.68; p = 0.000; I-square = 92.9 %), and the pooled specificity was 0.95 (95 % CI: 0.94 to 0.95; p = 0.000; I-square = 97.1 %). The sensitivity and specificity of these studies are summarized in forest plots (Fig. 5a and b). The AUC of the SROC curve was 0.83 (Fig. 6).

4. Discussion

This systematic review and meta-analysis is the first evaluation of the accuracy of near-infrared reflectance (NIRR) in proximal caries detection. Our findings reveal that NIRR exhibits limited pooled sensitivity for proximal caries detection in both *in vitro* (0.46, 95 % CI: 0.42 to 0.50) and clinical (0.65, 95 % CI: 0.62 to 0.68) studies. In contrast, the specificity of NIRR detection was generally high in both *in vitro* (0.87, 95 % CI: 0.84 to 0.89) and clinical (0.95, 95 % CI: 0.94 to 0.95) studies.

When evaluating results generated from *in vitro* studies and clinical studies, higher sensitivity and specificity values were found in clinical studies. This discrepancy could be explained by the absence of a gold reference standard for assessing proximal caries in clinical situations. Most clinical studies use bitewing radiography (BWR) as a reference standard [32,33,36,38], while *in vitro* studies typically employ micro-computed tomography (μCT) or histological examination [30,34,35,37,39,41], which are more reliable and accurate reference standard. Several *in vitro* studies comparing BWR and NIRR with reference standards have shown that NIRR performs comparably or even better than BWR [30,34,35,37,39]. This suggests that using BWR as a reference standard could potentially overstate the performance of NIRR.

Compared to previous literature, a meta-analysis of six studies showed that NIRT demonstrated overall good accuracy compared to bitewing radiographs, with a pooled sensitivity of 0.97 (95 % CI: 0.96–0.98) and specificity of 0.91 (95 % CI: 0.91–0.92) in clinical studies [42]. This sensitivity was higher than that obtained from NIRR in clinical studies in our review, which showed a pooled sensitivity of 0.65 (95 % CI: 0.62–0.68). However, this does not necessarily indicate that NIRT has a higher accuracy potential than NIRR. Several factors might explain this observation. First, in the NIRT meta-analysis, the six included studies used different cutoff values for diagnosis—five studies used enamel and one used dentin. For our review, all clinical studies used enamel as the cutoff value. Diagnosing enamel caries is more challenging than dentin caries due to its structure and appearance. Four studies comparing diagnostic accuracy for NIRR at different thresholds found that the threshold at dentin caries showed higher sensitivity and specificity than the threshold at enamel caries [32,36–38]. Second, while the NIRT meta-analysis exclusively used BWR as reference standards, the NIRR meta-analysis employed multiple reference standards, including μCT, visual and tactile assessment, BWR, PLM, and TMR. These differences in reference standards might have affected pooled sensitivity. Additionally, two clinical studies directly compared NIRT and NIRR diagnostic accuracy. One study found similar results between them: NIRT had a sensitivity of 0.23 (95 % CI: 0.1–0.42) and specificity of 0.91 (95 % CI: 0.83–0.96), while NIRR had a sensitivity of 0.27 (95 % CI: 0.12–0.46) and specificity of 0.92 (95 % CI: 0.84–0.97) [21]. Another study found different results: NIRT had lower accuracy (0.63) compared to NIRR (0.83), with NIRT showing sensitivity of 0.63 and specificity of 0.62, while NIRR showed sensitivity of 0.72 and specificity of 0.86 [40]. Therefore, further studies are needed to investigate the accuracy potential of NIRT and NIRR.

The lower sensitivity observed in this study does not undermine the potential of NIRR in proximal caries detection. Currently, the commercially available NIRR systems adopt near-infrared light of shorter wavelength (850 nm). The enamel transparency is generally low under the 850 nm NIRR due to the absorption and scattering properties of enamel at this wavelength. Enamel consists of hydroxyapatite crystals, which have specific light absorption and scattering characteristics. At shorter wavelengths such as 850 nm, light is absorbed more and scattered more extensively by the enamel, reducing its transparency. Therefore, the NIRR images obtained at these wavelengths may not provide enough resolution to distinguish between healthy and demineralized enamel [43,44]. However, previous studies indicate that the contrast between healthy and demineralized enamel significantly improves using NIRR of wavelengths beyond 1400 nm [22,45–47], demonstrating the potential of these longer wavelengths in improving the accuracy and reliability of NIRR systems in caries detection.

Despite the current limitations in the commercial availability of NIRR systems operating beyond 1000 nm, recent advances and findings suggest a promising future for these devices in improving caries diagnostics. NIRR devices operating beyond 1000 nm are not currently available, largely due to military restrictions and high costs. However, with significant cost reductions expected in the near future, this scenario is likely to change [44]. Studies published within the past two years have explored the accuracy of NIRR at higher wavelengths, yielding promising results: sensitivity of 0.73 and specificity of 0.76 at 1550 nm [30], sensitivity of 0.72 and specificity of 0.86 at 1600 nm [40]. However, one study was conducted *in vitro* and may not fully replicate the condition of the oral environment. Therefore, further investigation in clinical settings is warranted to validate these findings.

When considering the clinical application of NIRR, accuracy is not the only significant factor. Unlike radiographs, NIRR eliminates radiation exposure and reduces examination time [24]. However, it currently has limitations—primarily high equipment costs and the requirement for professional operation and maintenance to ensure proper use and safety [24]. Therefore, clinicians and researchers must consider both accuracy and cost-effectiveness. A recent study demonstrated this potential by developing low-cost, simple-to-use, non-contact, family-based oral health monitoring tools that integrate NIRR for caries detection [23]. Furthermore, NIRR imaging is especially suitable for integration with artificial intelligence (AI), as its enhanced lesion contrast and absence of stain interference offer key advantages for AI-based caries detection. Future research should explore combining NIRR with automated AI detection systems to create family-based oral health monitoring tools for caries prevention.

Significant heterogeneity was observed in the meta-analysis results. This heterogeneity can be attributed to several influencing factors, including variations in study design, differences in devices and wavelengths used, inconsistent thresholds, differing reference standards, and varying levels of examiner experience. Studies have demonstrated that these factors can affect accuracy results [30,38]. In examining wavelength specifically, one study compared 1050 nm and 1550 nm wavelengths while maintaining all other study parameters constant, revealing significant differences in accuracy [30]. The 1050 nm wavelength achieved a sensitivity of 0.44 (95 % CI: 0.41–0.47) and specificity of 0.96 (95 % CI: 0.85–1.06), while the 1550 nm wavelength showed a sensitivity of 0.73 (95 % CI: 0.66–0.80) and specificity of 0.76 (95 % CI: 0.67–0.85) [30]. This difference in wavelength alone can significantly affect the accuracy and contribute to the overall heterogeneity.

This review has several limitations. First, we included a relatively small number of studies in the review and meta-analysis. This limited sample size prevented subgroup analysis, particularly for different wavelengths. Moreover, high heterogeneity and potential bias risk restricted the broader applicability of our meta-analytical results. We also acknowledge that the findings from the included *in vitro* studies may not fully translate to real-world clinical settings. Nonetheless, their inclusion was carefully considered. While clinical studies offer patient-centred insights, many relied on bitewing radiography as the reference standard, which is not regarded as a true gold standard. In contrast, the *in vitro* studies employed micro-CT or histological examination, methods that provide more precise and objective reference standards. These *in vitro* findings therefore complement the clinical data and strengthen the overall evidence base. Furthermore, we used the QUADAS-2 tool to assess the quality of both clinical and *in vitro* studies. Although this tool was originally designed for clinical diagnostic accuracy studies, it has been applied in previous *in vitro* diagnostic evaluations [11,48]. However, we recognise that certain quality considerations unique to *in vitro* designs may not have been fully captured by this framework. Readers should bear this in mind when interpreting the quality assessments of the *in vitro* studies included in this review.

5. Conclusion

In conclusion, current evidence suggests that NIRR shows high specificity but low sensitivity when detecting proximal dental caries in posterior teeth. However, due to the high heterogeneity among studies, careful interpretation of the findings is necessary. Further research, especially with longer wavelengths, is needed to validate NIRR's potential in caries detection.

CRediT authorship contribution statement

Kaijing Mao: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Jason Chi-Kit Ku:** Validation, Methodology, Formal analysis, Data curation. **Feifei Wang:** Writing – review & editing, Validation. **Ke Song:** Writing – review & editing. **Walter Yu-Hang Lam:** Writing – review & editing, Validation, Supervision, Conceptualization. **Ollie Yiru Yu:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2025.105949.

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