Journal of Dentistry 157 (2025) 105737

Contents lists available at ScienceDirect

Journal of Dentistry

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

Review article

Accuracy of clinical photography for the detection of dental caries: A systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Dental caries
Clinical photography
Diagnostic accuracy
Caries detection
Teledentistry
Digital dentistry

ABSTRACT

Objective: To evaluate the accuracy of visual caries detection using clinical photographs in comparison with visual clinical intraoral examination for the detection of dental caries.
Data: This review followed PRISMA-DTA guidelines and was registered in PROSPERO (CRD42024598814). Accuracy parameters of sensitivity, specificity and diagnostic odds ratio (DOR), area under summary receiver operating characteristic curve (AUC), and partial AUC (pAUC) were generated. Risk of bias was assessed using QUADAS-2 tool.
Sources: Publications from PubMed, Web of Science, Scopus, and EMBASE databases.
Study selection/results: Eighteen studies including 1300 participants were included in this review. Risks of bias and applicability concerns were frequently encountered in one or more domains. The pooled sensitivity (95 % Confidence Interval, CI), specificity (95 %CI), DOR (95 %CI) and AUC (pAUC) of the visual assessment of clinical photographs were 0.74 (0.70–0.77), 0.95 (0.88–0.98), 52.94 (22.13–126.66), and 0.813 (0.753) for enamel caries; 0.81 (0.75–0.86), 0.98 (0.94–0.99), 142.01 (67.50–298.77), and 0.935 (0.857) for dentine caries; 0.81 (0.70–0.89), 0.99 (0.96–1.00), 245.04 (83.75–716.96), and 0.957 (0.902) for any caries depth. Subgroup analysis suggested that caries depth (enamel caries v.s. dentine caries v.s. any caries depth; $p = 0.072$), dentition (primary v.s. permanent; $p = 0.584$ (dentine caries data), $p = 0.923$ (any caries data)), technology (smartphone camera v.s. intra-oral camera; $p = 0.993$), and photographer (dental professional v.s. layperson; $p = 0.466$) did not modify the diagnostic performance.
Conclusions: Visual assessment of clinical photographs for caries detection demonstrated clinically acceptable accuracy when compared with visual clinical intraoral examination. High specificity values across diagnostic thresholds suggest a high level of accuracy in correctly identifying sound tooth structure.
Clinical significance: Clinical photography is useful for dental caries detection and can facilitate clinical decision-making.

1. Introduction

Dental caries is a multifactorial, non-communicable disease which results in net mineral loss from dental hard tissues [1]. This condition is largely preventable; yet, if left undiagnosed and untreated, it can result in a significant oral health burden [2]. Detecting and diagnosing dental caries at its early stage is the premise of proper caries management when cost-effective caries control strategies are still available. Thus, early and accurate detection of dental caries is crucial for releasing the oral health burden caused by dental caries [3,4].

In routine clinical practice, caries detection has traditionally relied on visual examination of caries presentation and surface characteristics. Visual or visual-tactile examination not only demonstrates reasonable diagnostic performance in detecting caries but also plays a pivotal role in informing clinically relevant treatment decisions [5,6]. However, the effectiveness of on-site clinical intraoral examination is limited by challenges such as patient accessibility to the dental clinic and subjectivity dependent on the clinician's experience in a clinical setting.

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https://doi.org/10.1016/j.jdent.2025.105737
Received 9 March 2025; Received in revised form 3 April 2025; Accepted 5 April 2025
Available online 7 April 2025

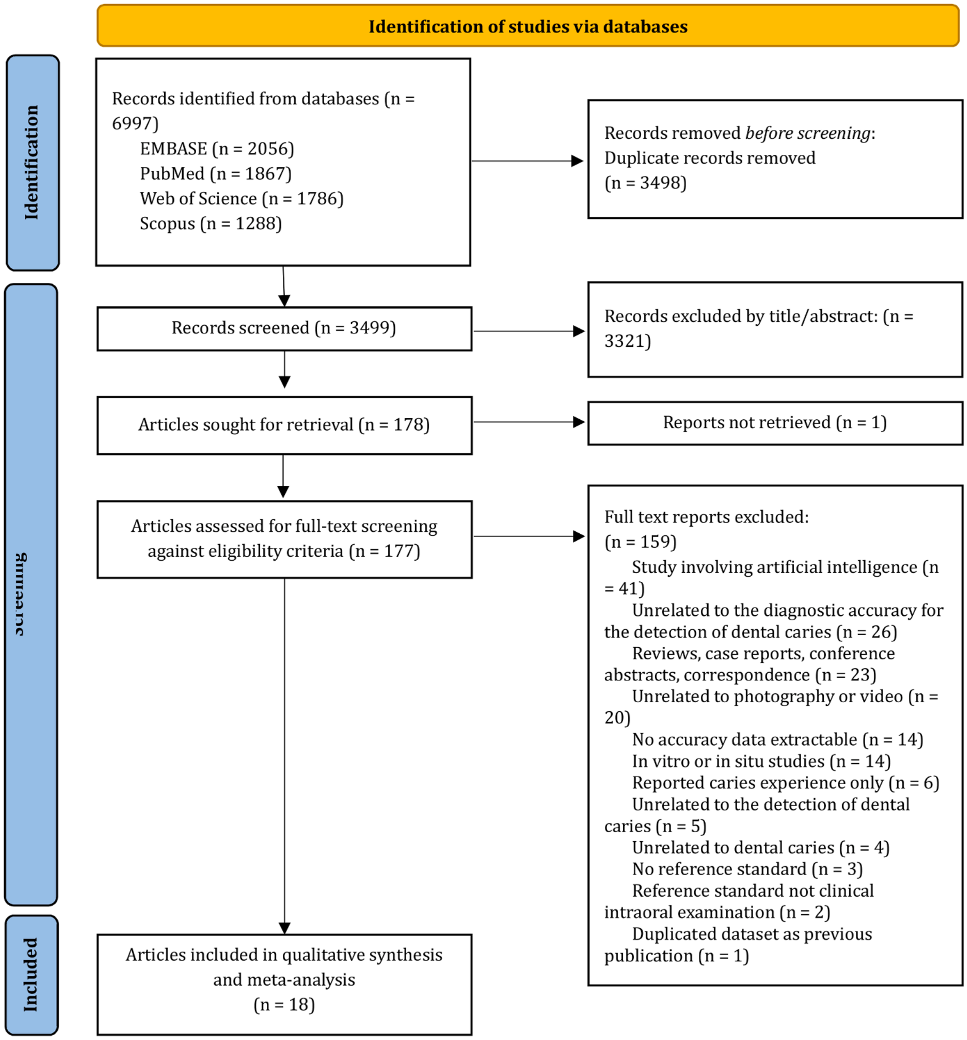

Fig. 1. PRISMA flowchart.

Consequently, the use of clinical photography for caries diagnosis has surged in conjunction with the growing interest in teledentistry, particularly since the Coronavirus disease 2019 (COVID-19) pandemic [7–9]. The advent of teledentistry technology enables clinicians to deliver dental care through remote consultation and diagnosis to patients in need, regardless of their access to a physical dental clinic [10]. The concept of remote diagnosis, or telediagnosis of dental caries, which incorporates digital-aided diagnostic methods, has been recognized for its potential to facilitate treatment recognition and enhance patient care [11,12]. Clinical photography plays a critical role as a key technology for the remote diagnosis of dental caries. Through an asynchronous store-and-forward process, clinical photographs and relevant information captured by healthcare professionals or patients are sent to a third party for diagnosis or treatment guidance [11]. Beyond its application in teledentistry, the ability to store clinical photographs allows for the documentation of the progression of caries lesions over time, aiding in the monitoring of treatment efficacy [13]. Moreover, visual evidence of caries captured through clinical photography can encourage patients to adhere to treatment strategies and facilitate interprofessional communication in the management of patients with medical conditions which may impact their caries status [14,15]. Lastly, the use of clinical photography for caries detection supports training in dental education settings and simplifies inter-examiner calibration in epidemiological contexts [16,17].

Nevertheless, the diagnostic efficacy of the visual detection method on clinical photographs remains an area that requires further exploration and correlation with established clinical reference standards. Previous systematic reviews in the literature have narratively assessed the diagnostic accuracy of visual caries detection using clinical photographs and concluded that the reviewed studies demonstrated comparable diagnostic performance to traditional on-site clinical examination [17–20]. Lee et al., Priyank et al., and Thanh et al. conducted meta-analyses to generate summary accuracy data supporting the efficacy of teledentistry [13,21,22]. Despite these valuable insights, the breadth of investigation could be expanded, and more relevant studies have emerged subsequent to the publication of these reviews. Therefore, a more comprehensive systematic review and a more statistically robust meta-analysis would be invaluable. Hence, the aim of this systematic review and meta-analysis was to evaluate the accuracy of visual caries detection using clinical photographs in comparison with visual clinical intraoral examination for the detection of dental caries.

2. Materials and methods

2.1. Research questions and protocols

This systematic review answers the research question, “What is the accuracy of visual caries detection using clinical photographs in comparison with visual clinical intraoral examination for the detection of dental caries?” The research question was created using the PICO

Table 1
Summary characteristics of included studies.

Study (Country)	Sample size (teeth, patients, photographs)	Dentition	Type of image (complete/ single tooth)	Technology[a]	Photographer involved[b]	Photographic examination criteria	Diagnostic threshold[c]	Sensitivity/ Specificity
Almosa 2014 (Sweden)	245, 89, 245	Permanent	Single tooth	DSLR	PRO	ICDAS	Enamel caries Dentine caries Any caries	0.80/0.79 0.67/0.92 0.94/0.80
Aly 2024 (Egypt)	2243, 116, n/a	Primary	Smartphone: Complete; IOC: Single tooth	Smartphone, IOC*	PRO	CAST	Enamel caries Dentine caries Any caries	0.72/0.95 0.91/0.98 0.88/1.00
Ashtiani 2024 (Iran)	3015, 131, 977	Mixed*	Complete	Smartphone	PRO	ICDAS	Dentine caries	0.81/0.96
Azimi 2023 (Australia)	844, 44, 370	Primary	Complete	Smartphone	LP	ICDAS	Any caries	0.67/0.98
Boye 2013 (UK)	2442, 123, n/a	Primary	Single tooth	IOC	PRO	BASCD	Dentine caries	0.92/0.89
Elfrink 2009 (Netherlands)	496, 62, n/a	Primary	Single tooth	IOC	PRO	WHO	Dentine caries	0.85/0.84
Estai 2016 (Australia)	2707, 100, 500	Primary, mixed, permanent	Complete	Smartphone	PRO	WHO	Any caries	0.60/0.98
Estai 2022 (Australia)	3105, 138, 690	Primary, mixed	Complete	Smartphone	PRO	WHO	Any caries	0.68/1.00
Golsanamloo 2022 (Iran)	480, 20, 100	Mixed	Complete	Smartphone	PRO	Binary system on caries presence or absence	Dentine caries	0.77/0.93
Hu 2016 (Netherlands)	115, 36, n/a	Permanent	Complete	DSLR	PRO	Binary system on caries presence or absence	Enamel caries	0.78/0.89
Kale 2019 (India)	2000, 100, 300	Primary	Complete	Smartphone	PRO	WHO	Dentine caries	0.88/0.98
Kohara 2018 (Brazil)	119, 15, n/a	Primary	Complete	Smartphone, DSLR	PRO	ICDAS	Any caries	0.58/1.00
Kuppusamy 2024 (Malaysia)	442, 19, n/a	Mixed	Complete	Smartphone	PRO	ICDAS	Enamel caries Dentine caries Any caries	0.75/0.98 0.71/1.00 0.76/0.98
Morosini 2014 (Brazil)	3264, 102, n/a	Permanent	Complete	DSLR	PRO	WHO	Dentine caries	0.73/0.98
Qari 2024 (Saudi Arabia)	644, 23, 108	Permanent	Complete	Smartphone	Both PRO and LP *	WHO	Any caries	0.90/0.90
Sardana 2022 (Hong Kong)	1607, 99, n/a	Permanent	Complete	DSLR	PRO	Gorelick	Any caries	0.96/0.99
Thomas 2021 (UK)	788, 40, 120	Primary	Single tooth	IOC	PRO	BASCD	Dentine caries	0.62/1.00
Zotti 2022 (Italy)	1201, 43, 215	Permanent	Complete	Smartphone	LP	ICDAS	Enamel caries Dentine caries Any caries	0.70/0.98 0.75/0.99 0.74/0.99

n/a: data not available or applicable.
[a] Technology used for taking photographs, including digital single lens reflex (DSLR) cameras, intra-oral cameras (IOC), and smartphones.
[b] Photographs taken by either dental professionals (PRO) or by layperson (LP).
[c] Enamel caries is defined as caries limited only to enamel, dentine caries as caries involving both enamel and dentine, any caries as caries involving either enamel or both enamel and dentine.
* Data available to be pooled separately for subgroup analysis.

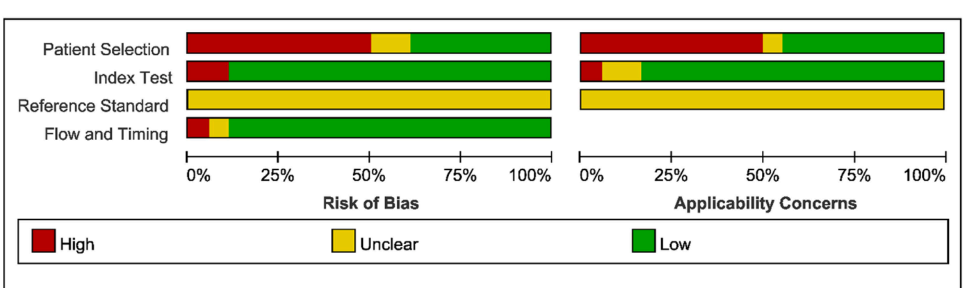

Fig. 2. Summary of QUADAS-2 risk of bias and applicability concern assessment. The proportion of included studies with low, unclear, or high risk of bias or applicability concerns in each domain are shown (%).

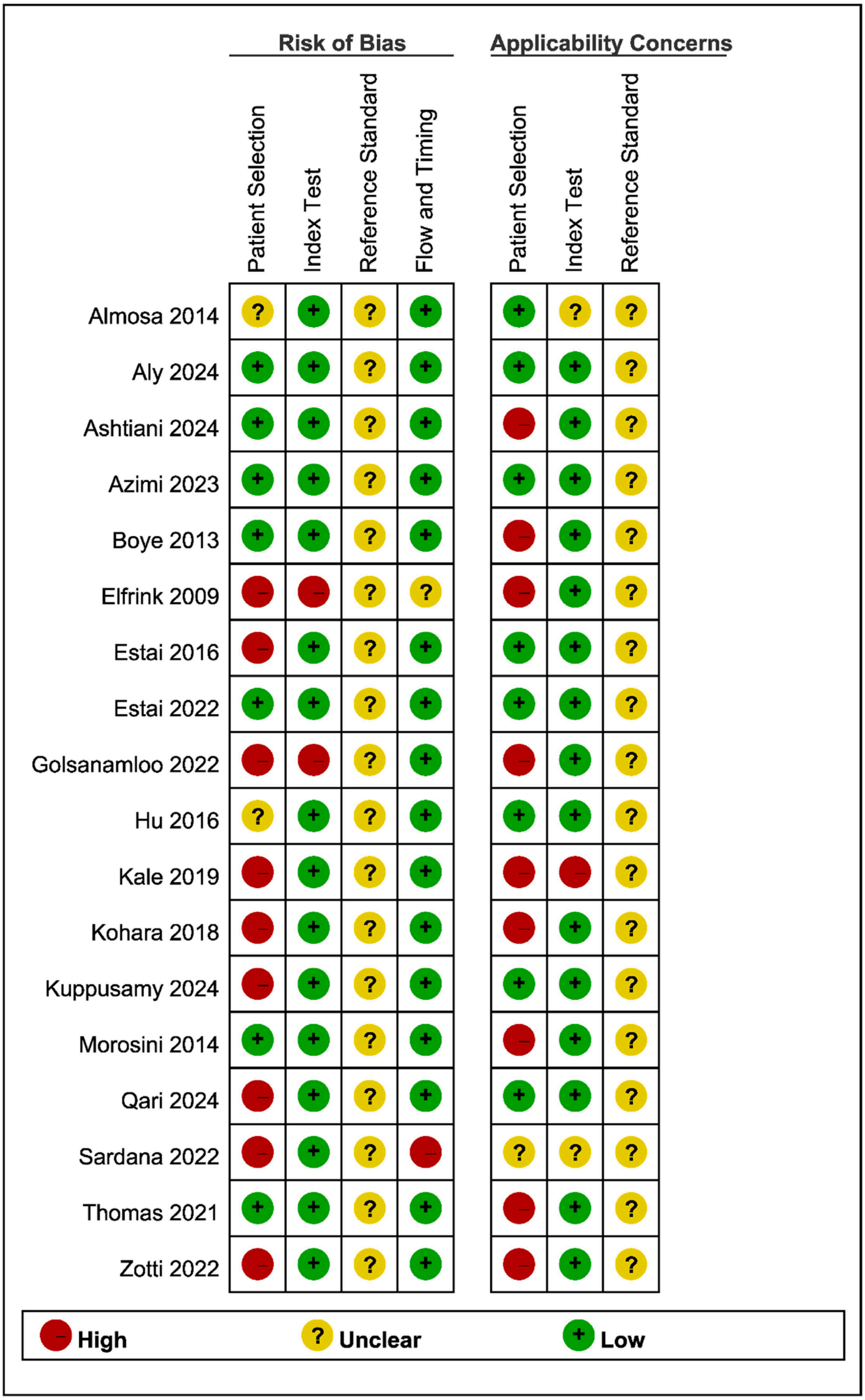

Fig. 3. Individual judgments for risk of bias and applicability concern domains using QUADAS-2.

strategy: (P) population — dental caries; (I) intervention — visual caries detection using clinical photographs; (C) comparison — visual clinical intraoral examination; (O) outcome — diagnostic accuracy parameters, including sensitivity, specificity, diagnostic odds ratio, and area under summary receiver operating characteristic curve.

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis of Diagnostic Test Accuracy Studies (PRISMA-DTA) guidelines [23,24]. The PRISMA-DTA checklists are available in the supplementary materials. This study was registered in the International Prospective Register of Systematic Reviews (PROSPERO Registration ID: CRD42024598814).

Table 2
Results of random-effects meta-analysis. DOR: diagnostic odds ratio; 95 %CI: 95 % confidence interval; I^2: I-square statistic; $p_{subgroup}$: p-value of the test for subgroup differences.

Subgroups	No. of subgroups*	Teeth no.	Sensitivity (95 % CI)	$I^2_{(Sensitivity)}$, %	Specificity (95 % CI)	$I^2_{(Specificity)}$, %	DOR (95 %CI)	$I^2_{(DOR)}$, %	AUC (pAUC)	$p_{subgroup}$ (Sensitivity)	$p_{subgroup}$ (Specificity)	$p_{subgroup}$ (DOR)
Enamel caries	5	3771	0.74(0.70–0.77)	0	0.95(0.88–0.98)	95	52.94 (22.13–126.66)	87	0.813 (0.753)	0.061	0.181	0.072
Dentine caries	11	16,616	0.81(0.75–0.86)	88	0.98(0.94–0.99)	97	142.01 (67.50–298.77)	92	0.935 (0.857)			
Any caries	10	13,157	0.81(0.70–0.89)	94	0.99(0.96–1.00)	96	245.04 (83.75–716.96)	90	0.957 (0.902)			

2.2. Search strategy

Electronic databases of PubMed, Web of Science, Scopus, and EMBASE were searched. The search was performed on January 1st, 2025. No date or language restrictions were applied. The search procedures were customized for all databases. The search strategy was as follows.

#1 “caries” OR “tooth decay”
#2 “phone” OR “camera” OR “photograph*” OR “photo” OR “photos” OR “intraoral photography” OR “video*” OR “telediagnosis” OR “telemedicine” OR “teledentistry” OR “telehealth” OR “teleconsultation” OR “tele*” OR “remote” OR “remote consultation” OR “mobile” OR “mHealth” OR “eHealth”
#3 “#1″ AND “#2”

2.3. Studies selection

The identified articles were transferred to Covidence software. Duplicate data was removed after which two reviewers (JCKK, KM) independently screened the titles and abstracts. Full texts of potentially relevant studies were evaluated for eligibility. Disagreements were resolved by consultation with the third and fourth reviewers (WYHL, OYY).

2.4. Eligibility criteria

2.4.1. Inclusion criteria

The inclusion criteria were studies that

- evaluated primary or secondary dental caries, not including residual caries
- evaluated the non-histological and visual caries detection on intact human teeth using any photographs or videos
- used visual clinical intraoral examination as a reference standard
- reported parameters evaluating diagnostic accuracy, including sensitivity, specificity, diagnostic odds ratio, and area under curve
- were conducted in vivo
- were conducted in any language, date and sample size

2.4.2. Exclusion criteria

The exclusion criteria were studies that

- reported tooth demineralization irrelevant to dental caries
- used ancillary detection technology, e.g. fluorescence, artificial intelligence
- applied visual photographic reference standard
- reported incomplete accuracy parameters leading to failure to extract values of true positive, false positive, false negative and true negative results
- were reviews, case reports, conference abstracts, correspondence, protocols, or inaccessible

2.5. Data collection

Two reviewers (JCKK, KM) extracted data from the included studies. Any discrepancies were resolved through consultation with the third and fourth reviewers (WYHL, OYY). The following data were extracted using Excel software (Excel, Microsoft, Redmond, WA, USA): bibliographic details (first author, country, year of publication); sample size (number of teeth, patients and photographs taken); dentition; photographic views; tooth surface investigated; lesion type; photographic technology used; criteria for photographic analysis; diagnostic threshold; criteria for reference standard; accuracy parameters (i.e. true positive, false positive, false negative and true negative values,

Table 3
Results of subgroup analysis. DOR: diagnostic odds ratio; 95 %CI: 95 % confidence interval; I^2: I-square statistic; $p_{subgroup}$: p-value of the test for subgroup differences.

	Subgroups	No. of subgroups#	Teeth no.	Sensitivity (95 % CI)	$I^2_{(Sensitivity)}$, %	Specificity (95 % CI)	$I^2_{(Specificity)}$, %	DOR (95 %CI)	$I^2_{(DOR)}$, %	$p_{subgroup}$ (Sensitivity)	$p_{subgroup}$ (Specificty)	$p_{subgroup}$ (DOR)
Dentition*	Permanent	4	6143	0.79(0.65–0.89)	77	0.97(0.93–0.99)	95	115.14 (36.72–361.01)	84	0.169	0.738	0.584
	Primary	6	9551	0.88(0.81–0.92)	87	0.96(0.89–0.99)	97	174.58 (67.34–452.58)	94			
Dentition**	Permanent	4	8239	0.91(0.81–0.96)	92	0.96(0.85–0.99)	97	211.52 (48.56–921.41)	92	0.044	0.102	0.923
	Primary	3	4868	0.74(0.55–0.87)	96	1.00(0.95–1.00)	83	257.12 (6.64–9959.11)	90			
Technology*	Smartphone	6	8239	0.82(0.78–0.86)	72	0.98(0.96–0.99)	89	200.80 (82.69–487.58)	89	0.384	0.476	0.993
	IOC	4	4868	0.88(0.74–0.95)	92	0.97(0.85–0.99)	96	202.67 (36.40–1128.47)	95			
Photographer**	Professional	8	11,112	0.83(0.71–0.91)	95	0.99(0.95–1.00)	96	272.38 (68.20–1087.79)	92	0.955	0.410	0.466
	Layperson	3	2689	0.82(0.63–0.93)	92	0.97(0.91–0.99)	96	152.51 (74.59–311.82)	62			

* Data pooled from studies assessing dentine caries.
** Data pooled from studies assessing any caries depth.
# When available, data was collected and pooled separately in studies investigating more than one subgroup.

sensitivity, specificity, and caries prevalence).

Regarding diagnostic thresholds, "enamel caries" is defined as a detectable change in enamel that is not thought to have progressed into dentine at the point of detection. Under the International Caries Detection and Assessment System (ICDAS), "enamel caries" includes both incipient non-cavitated caries (i.e. ICDAS 1–2) and caries with enamel micro-cavitation with no dentine involvement (i.e. ICDAS 3). "Dentine caries" is defined as a detectable change in enamel that is thought to have extended into dentine at the point of detection, encompassing ICDAS 4–6 caries. "Any caries depth" includes both "enamel caries" and "dentine caries".

Sensitivity, specificity and tooth-level caries prevalence were extracted in each study, with reference to the three diagnostic thresholds. In studies reporting more than one threshold, accuracy parameters were calculated from primary datasets to differentiate caries detection in different caries depth. For studies with more than one examiner, the values from all examiners were averaged. True positive, false positive, false negative, and true negative values were collected for meta-analysis in each study.

2.6. Assessment of the quality and risk of bias assessment of the studies

The quality of included studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) tool [25]. Risk of bias was assessed in four domains: 1) patient selection - consecutive or random inclusion, no case-control designs, no inappropriate exclusions; 2) index test (clinical photography) - pre-defined diagnostic threshold, index test blinded for and independent of reference test; 3) reference standard (visual clinical intraoral examination) - reference test blinded and independent of index test; 4) flow and timing - appropriate inclusion of samples, and appropriate intervals between index test and reference standard. In addition, applicability assessments were conducted for the initial three domains: 1) patient selection - study setting, lesion spectrum, realistic caries prevalence; 2) index test - test technology, conduct and interpretation matching the research question; 3) reference standard – the condition identified by a reference standard matches the research question. Any concern was categorized as "low", "unclear" or "high" for each domain.

2.7. Data synthesis and meta-analysis

2.7.1. Univariate meta-analysis

Accuracy parameters from each diagnostic threshold (enamel caries, dentine caries, any caries depth) were analyzed using a generalized linear mixed model, with mixed-effects logistic regression. Mean sensitivity and specificity values were extracted at tooth level from each study. Sensitivity, specificity and diagnostic odds ratio (DOR) were logit-transformed and then reverted for interpretation. 95 % confidence intervals (95 %CI) were produced. Inverse-variance weighting was applied for DOR pooling. Maximum-likelihood model was used for sensitivity and specificity. A continuity correction of 0.5 was applied in studies with zero cell frequencies. Graphical representation was constructed using forest plots of DOR.

Subgroup analyses were performed using the random effect model. Pre-specified groups of diagnostic thresholds (enamel caries, dentine caries, any caries depth), dentition (primary, permanent, mixed), photographic technology (digital single-lens reflex camera (DSLR), intra-oral camera (IOC), smartphone camera), and professional background of the photographer (dental professional, layperson) were analyzed separately. The latter three subgroups were conducted for each diagnostic threshold. If available, data was collected and pooled separately in studies investigating more than one subgroup. A minimum of 3 studies in each subgroup served as the minimum for consideration of subgroup analysis.

Table 4
Results of heterogeneity measures. SE: sensitivity; SP: specificity; Tau^2: between-study variance; MOR: median odds ratio; rho: Spearman's correlation coefficient.

	Heterogeneity statistic estimates								
	Q(DOR;p-value)	I^2(DOR), %	Tau^2 (logit SE)	Tau^2 (logit SP)	MOR (SE)	MOR (SP)	95 % Prediction ellipse area	Rho (p-value)	Deek's (p-value)
Enamel caries	30.74(< 0.0001)	87	0.03	1.05	1.17	2.65	0.228	–	–
Dentine caries	133.99(< 0.0001)	92	0.34	2.03	1.74	3.89	0.186	0.427(0.193)	0.883
Any caries	91.76(< 0.0001)	90	0.82	2.79	2.37	4.91	0.214	0.006(1.000)	0.015

2.7.2. Bivariate meta-analysis

Random-effects bivariate analysis was conducted using the model of Reitsma et al. [26]. Summary receiver operating characteristics (sROC) curve was fitted by restricted maximum-likelihood estimation and plotted with 95 % confidence regions. The area under sROC curve (AUC) and partial AUC restricted to observed false positive rates and normalized (pAUC) were evaluated.

2.7.3. Heterogeneity review

Heterogeneity for each diagnostic threshold was quantified using Cochran's Q (chi-squared test) and I^2 statistics under DOR models. Between-study variance (Tau^2) of logit sensitivity and specificity, the area of the 95 % prediction ellipse in sROC plane, and median odds ratio (MOR) were obtained [27]. MOR values range from 1 (no heterogeneity) to infinite (high heterogeneity).

Spearman's correlation analysis between sensitivity and false positive rates was conducted where $rho \geq 0.6$ indicates a considerable threshold effect [28]. Publication bias was visually assessed with Deeks' funnel plot asymmetry test designed for studies of diagnostic accuracy [29]. It plots the lnDOR against 1/effective sample size, and a p-value >0.10 suggests that publication bias is not detected. A minimum of ten studies in each diagnostic threshold served as the minimum for consideration of the above two tests.

Mixed-effects meta-regression analyses were used to explore the influence of pre-determined covariates (diagnostic threshold, dentition, photographic technology, photographer involved) on DORs. The latter three covariates were assessed for each diagnostic threshold. A minimum of 3 studies in each subgroup served as the minimum for consideration of meta-regression.

Statistical significance of p-value 0.05 was applied for all analyses except Cochran's Q test, Spearman's coefficient and Deeks' funnel test, where 0.10 was applied.

2.7.4. Software for data analysis

Data was analyzed with R 4.4.2 language and environment for statistical processing.

3. Results

3.1. Results of the search and study selection

The PRISMA flowchart is shown in Fig. 1. A total of 6997 studies were identified: 2056 studies from EMBASE, 1867 studies from PubMed, 1786 studies from Web of Science, and 1288 studies from Scopus. 3498 duplicated references were removed. Subsequently, 3499 studies were screened by title and abstract, of which 3321 studies were excluded. One study was not retrieved. 177 studies were assessed for eligibility, of which 159 studies were excluded with reasons. The reasons for exclusion are listed in Supplementary Table 1 and summarized in Fig. 1. Finally, 18 studies were included in this review [30–47].

3.2. Study characteristics

The summary characteristics of the included studies are listed in Table 1. These studies were all published in English between 2009 and 2024. The studies were published by teams from Australia ($n = 3$), Brazil ($n = 2$), Iran ($n = 2$), The Netherlands ($n = 2$), the United Kingdom ($n = 2$), Egypt ($n = 1$), Hong Kong ($n = 1$), India ($n = 1$), Italy ($n = 1$), Malaysia ($n = 1$), Saudi Arabia ($n = 1$), and Sweden ($n = 1$).

A total of 25,757 teeth were examined on 1300 patients. Visual clinical and visual photographic examinations were performed in permanent dentition ($n = 7$), mixed dentition ($n = 5$), or primary dentition ($n = 9$). One study reported accuracy parameters in two types of dentitions, while one reported accuracy parameters in three types of dentitions. Studies evaluated enamel caries only ($n = 5$), dentine caries only ($n = 11$) or any caries depth ($n = 10$). Data was available in four studies to extract accuracy parameters according to the three diagnostic thresholds.

For visual photographic examination, assessment criteria were used based on the International Caries Detection and Assessment System (ICDAS) [48] ($n = 6$), World Health Organization decayed teeth index ($n = 6$), British Association for the Study of Community Dentistry (BASCD) index [49] ($n = 2$), binary system on caries presence or absence ($n = 2$), Caries Assessment Spectrum and Treatment (CAST) index [50] ($n = 1$), or Gorelick index [51] ($n = 1$).

Photographs of the complete dentition were taken in 14 studies and the following views were taken in these studies: standard five views (upper and lower occlusal, left and right buccal, and frontal views) in 10 studies; three views (upper and lower occlusal, and frontal views) in 2 studies; three views (left and right buccal, and frontal views) in 1 study; and two views (upper and lower occlusal views) in 1 study. Photographs at the single-tooth level were taken in 5 studies and the following views were taken in these studies: occlusal views ($n = 3$), buccal view ($n = 1$), buccal, occlusal and lingual views ($n = 1$). One study has taken both photographs for single-tooth and dentition levels separately.

Smartphone cameras were used to capture photographs for caries detection in 11 studies, DSLR cameras in 5 studies, and IOC in 4 studies. Two studies assessed two types of photographic technologies separately. Photographs for caries detection in 16 studies were taken only by dental professionals, while photographs in 3 studies were taken only by laypersons. One study evaluated photographs taken only by dental professionals and photographs taken only by laypersons separately.

3.3. Quality and risk of bias of the included studies

Summary of QUADAS-2 analysis is presented in Fig. 2 and individual ratings are listed in Fig. 3. For risk of bias, the patient selection domain had the largest proportion of high-risk ratings reported ($n = 9$, 50 %). For the index test and flow and timing domains, risks of bias were considered low in 89 % ($n = 16$) and 89 % ($n = 16$) of studies respectively. All the included studies were rated with unclear risk of bias in the reference standard domain.

For applicability concerns, high concern was rated in 9 studies (50 %) regarding patient selection. Applicability concerns were low in the

Table 5
Results of meta-regression. Tau^2 represents estimated amount of residual heterogeneity; R^2 represents amount of heterogeneity accounted for by applying covariates; p-value of the test of moderators assesses if the covariate influences the studies' effect size.

	Tau^2 (Standard error)	R^2, in %	*p* of moderators
Diagnostic thresholds	1.651(0.560)	9	0.131
Dentition*	1.234(0.699)	0	0.597
Dentition**	4.327(3.024)	0	0.898
Technology*	1.757(1.015)	0	0.913
Photographer**	2.623(1.396)	0	0.597

* Data pooled from studies assessing dentine caries.
** Data pooled from studies assessing any caries depth.

index test domain of 15 studies (83 %). All of the included studies had unclear applicability concerns in the reference standard domain.

3.4. Quantitative meta-analysis

The summary statistics and the results of subgroup analyses are reported in Tables 2 and 3 respectively. Tables 4 and 5 report the results of heterogeneity measures and meta-regression. Forest plots of DOR values for each diagnostic threshold are presented in Fig. 4. Figs. 5 and 6 illustrate the sROC curves and Deeks' funnel plots, respectively.

Meta-analysis showed that visual detection of enamel caries using clinical photographs has a pooled sensitivity of 0.74 (95 %CI 0.70–0.77), specificity of 0.95 (95 %CI 0.88–0.98), DOR value of 52.94 (95 %CI 22.13–126.66), AUC value of 0.813, and pAUC value of 0.753. For visual detection of dentine caries using clinical photographs, the meta-analysis showed a pooled sensitivity of 0.81 (95 %CI 0.75–0.86), specificity of 0.98 (95 %CI 0.94–0.99), DOR value of 142.01 (95 %CI 67.50–298.77),

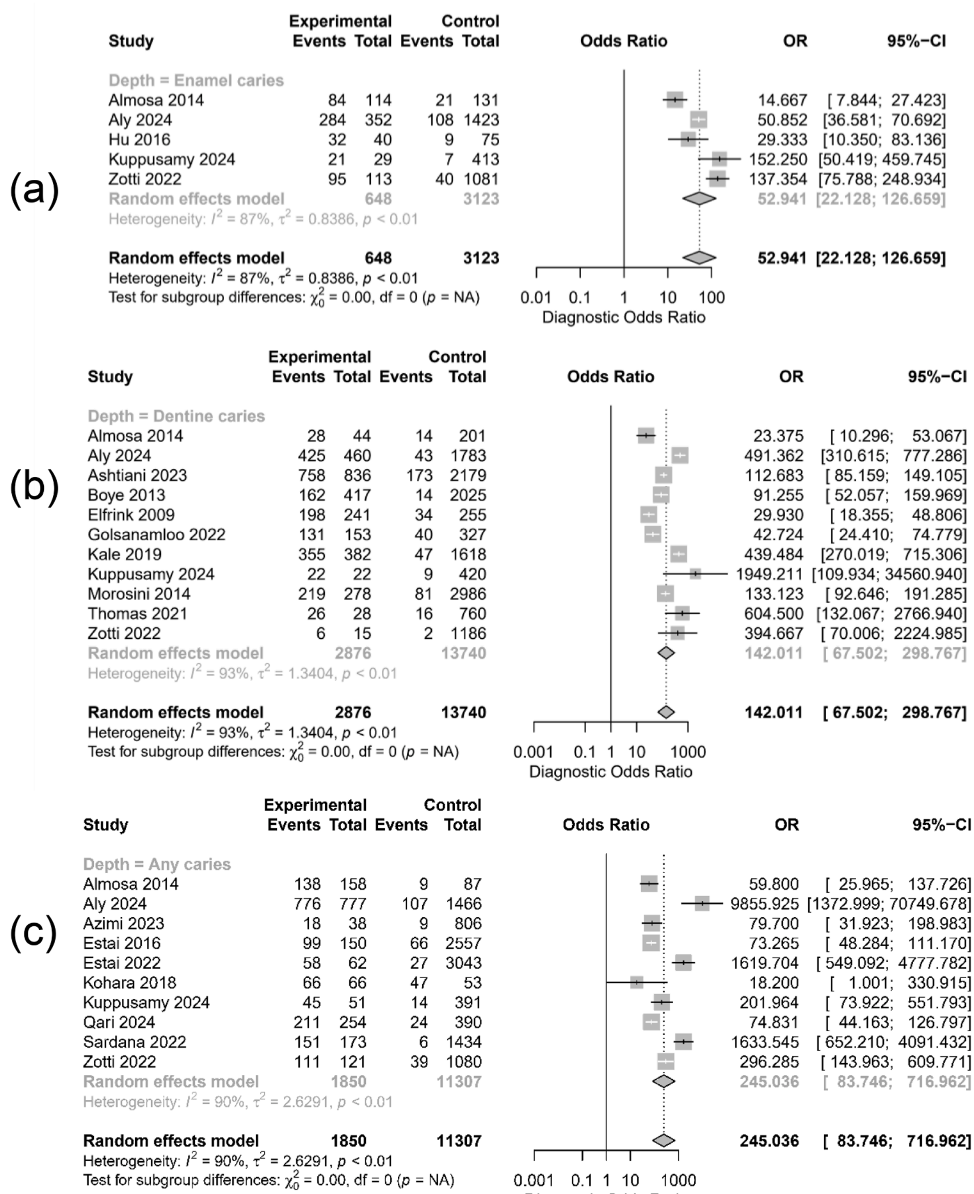

Fig. 4. Forest plots of (a) enamel caries, (b) dentine caries, and (c) any caries depth. For each study, a graphical representation of study weight (square), confidence interval (line), OR (DOR) values, and its 95 % confidence interval are provided. Experimental events (true positive values) and its total (true positive and false positive values) and control events (false negative values) and its total (false negative and true negative values) are also reported.

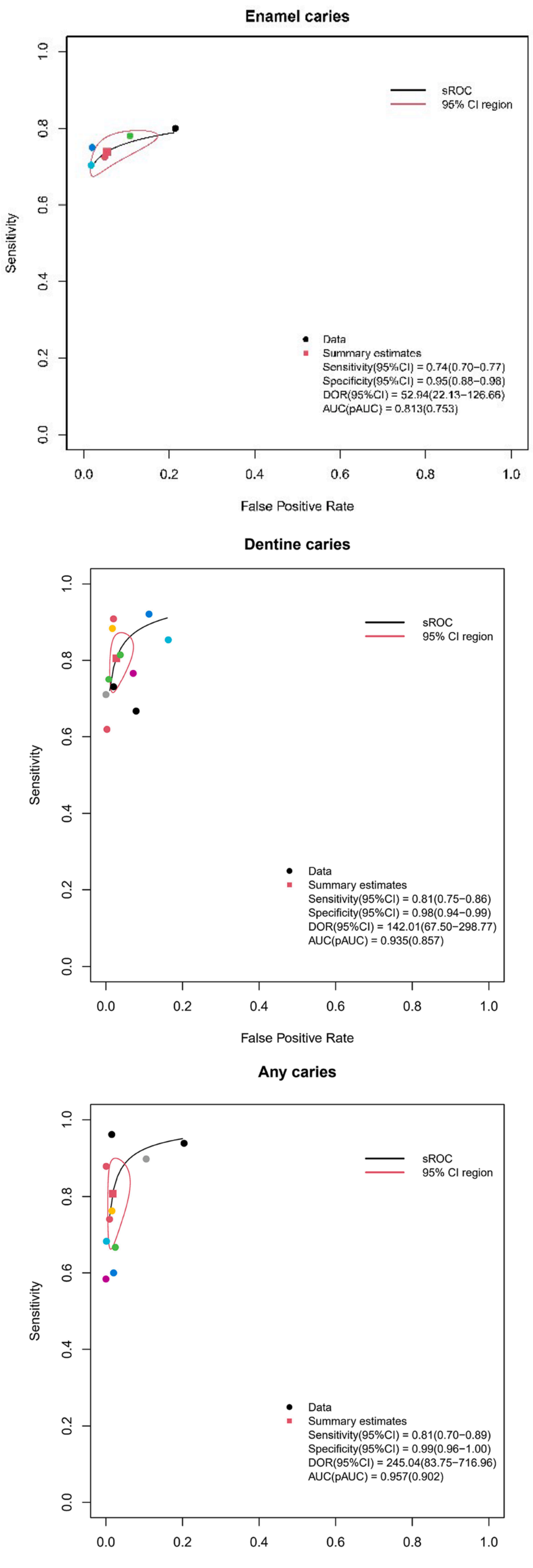

Fig. 5. Summary receiver operating characteristic (sROC) curve of enamel caries, dentine caries, and any caries in bivariate model. Sensitivity, specificity, diagnostic odds ratio, area under sROC curve (AUC) and partial AUC are reported.

AUC value of 0.935, and pAUC value of 0.857. For visual detection of any caries depth using clinical photographs, meta-analysis resulted in a pooled sensitivity of 0.81 (95 %CI 0.70–0.89), specificity of 0.99 (95 % CI 0.96–1.00), DOR value of 245.04 (95 %CI 83.75–716.96), AUC value of 0.957, and pAUC value of 0.902. Subgroup analyses of the effect of diagnostic thresholds on the diagnostic accuracy of visual caries detection on clinical photographs failed to show statistical significance among visually assessing enamel caries, dentine caries or caries at any depth (Sensitivity: $p = 0.061$; Specificity: $p = 0.181$; DOR: $p = 0.072$). The respective sample sizes were 3771 teeth, 16,616 teeth and 13,157 teeth for studies assessing enamel caries, dentine caries, and caries at any depth (Table 2; Figs. 4–5).

Subgroup analyses of the effect of dentition types on the diagnostic accuracy of visual detection of caries on clinical photographs were conducted according to the diagnostic thresholds of dentine caries depth and any caries depth groups. Subgroup analysis of the effect of dentition types in studies assessing enamel caries threshold was not conducted due to a lack of sufficient studies available for analysis. The test for subgroup differences (using dentine caries threshold) of the dentition types did not show statistical significance (Sensitivity: $p = 0.169$; Specificity: $p = 0.738$; DOR: $p = 0.584$). Visual assessment of clinical photographs on permanent dentition ($n = 6143$) demonstrated pooled sensitivity of 0.79 (95 %CI 0.65–0.89), specificity of 0.97 (95 %CI 0.93–0.99), and DOR of 115.14 (95 %CI 36.72–361.01) in detecting dentine caries. For primary dentition, visual assessment of clinical photographs ($n = 9551$) showed a pooled sensitivity of 0.88 (95 %CI 0.81–0.92), specificity of 0.96 (95 %CI 0.89–0.99), and DOR of 174.58 (95 %CI 67.34–452.58) in detecting dentine caries. Contrary to the dentine caries group, subgroup analysis of dentition involved (using any caries depth threshold) showed statistical significance in sensitivity value ($p = 0.044$), while specificity and DOR values did not (Specificity: $p = 0.102$; DOR: 0.923). Visual assessment of clinical photographs on permanent dentition ($n = 8239$) demonstrated pooled sensitivity of 0.91 (95 %CI 0.81–0.96), specificity of 0.96 (95 %CI 0.85–0.99), and DOR of 211.52 (95 %CI 48.56–921.41) in detecting any caries depth. For primary dentition, visual assessment on clinical photographs ($n = 4868$) showed a pooled sensitivity of 0.74 (95 %CI 0.55–0.87), specificity of 1.00 (95 %CI 0.95–1.00), and DOR of 257.12 (95 %CI 6.64–9959.11) in detecting any caries depth. Subgroup analyses of the diagnostic accuracy of visual assessment of clinical photographs on mixed dentition in studies assessing dentine caries threshold and any caries depth threshold were not conducted due to a limited number of available studies for analysis (Table 3).

The subgroup analysis investigating the effect of the types of photographic technology on the diagnostic accuracy of visually detecting caries in clinical photographs within studies evaluating dentine caries threshold revealed no statistically significant findings (Sensitivity: $p = 0.384$; Specificity: $p = 0.476$; DOR: $p = 0.993$). Subgroup analyses of the effect of photographic technology types were not conducted in studies assessing enamel caries threshold or any caries depth threshold due to an inadequate number of studies. Visual assessment of clinical photographs taken using smartphones ($n = 8239$) showed a pooled sensitivity of 0.82 (95 %CI 0.78–0.86), specificity of 0.98 (95 %CI 0.96–0.99), and DOR of 200.80 (95 %CI 82.69–487.58) in detecting dentine caries. Visual assessment of clinical photographs taken using IOC ($n = 4868$) showed pooled sensitivity of 0.88 (95 %CI 0.74–0.95), specificity of 0.97 (95 %CI 0.85–0.99), and DOR of 202.67 (95 %CI 36.40–1128.47) in detecting dentine caries. Subgroup analysis of the diagnostic accuracy of visual assessment of clinical photographs taken using DSLR cameras was not conducted due to a limited number of available studies for analysis (Table 3).

The subgroup analysis examining the influence of the professional background of the photographer on the diagnostic accuracy of visually detecting caries in clinical photographs within studies assessing any caries depth did not yield statistically significant results (Sensitivity: $p = 0.955$; Specificity: $p = 0.410$; DOR: $p = 0.466$). The subgroup analyses

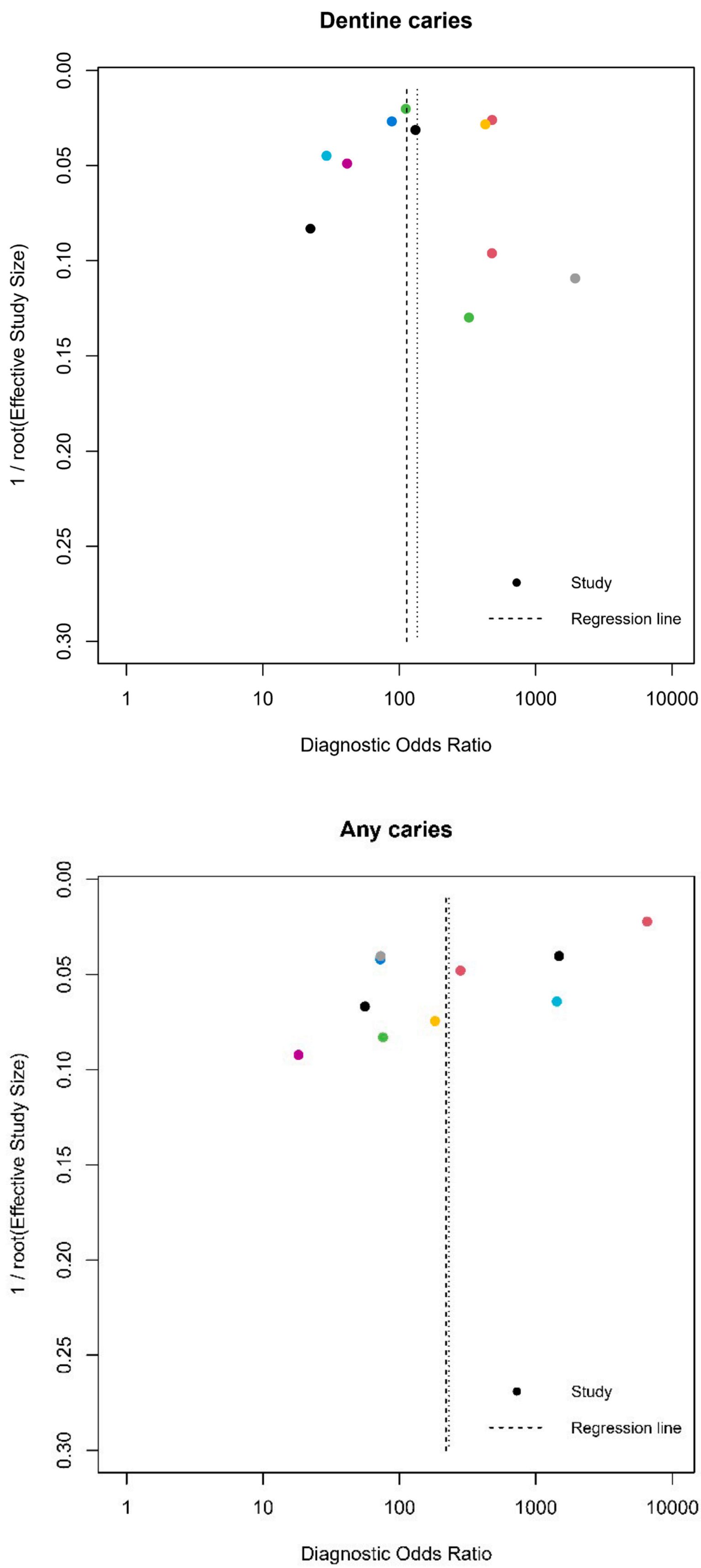

Fig. 6. Publication bias assessment of dentine caries group and any caries group using Deeks' funnel plots. The horizontal axis is the natural logarithm of DOR and vertical axis is the inverse of the square root of the effective sample size.

regarding the effect of professional background of the photographer in studies evaluating enamel caries threshold and dentine caries threshold were not performed due to insufficient studies. Visual assessment of clinical photographs taken by dental professionals ($n = 11{,}112$) showed pooled sensitivity of 0.83 (95 %CI 0.71–0.91), specificity of 0.99 (95 % CI 0.95–1.00), and DOR of 272.38 (95 %CI 68.20–1087.79) in detecting any caries depth. Visual assessment of clinical photographs taken by layperson ($n = 2689$) showed pooled sensitivity of 0.82 (95 %CI 0.63–0.93), specificity of 0.97 (95 %CI 0.91–0.99), and DOR of 152.51 (95 %CI 74.59–311.82) in detecting any caries depth (Table 3).

Heterogeneity measures of studies assessing the diagnostic accuracy of visually detecting enamel caries using clinical photographs reported Q (DOR; p-value) of 30.74 (<0.0001), I^2(DOR) of 87 %, Tau^2 (logit sensitivity) of 0.03, Tau^2 (logit specificity) of 1.05, MOR (sensitivity) of 1.17, MOR (specificity) of 2.65, and 95 % prediction ellipse area of 0.228. Heterogeneity measures of studies assessing the diagnostic accuracy of visually detecting dentine caries using clinical photographs reported Q (DOR; p-value) of 133.99 (<0.0001), I^2(DOR) of 92 %, Tau^2 (logit sensitivity) of 0.34, Tau^2 (logit specificity) of 2.03, MOR (sensitivity) of 1.74, MOR (specificity) of 3.89, and 95 % prediction ellipse area of 0.186. Heterogeneity measures of studies assessing the diagnostic accuracy of visually detecting any caries depth using clinical photographs reported Q (DOR; p-value) of 91.76 (<0.0001), I^2(DOR) of 90 %, Tau^2 (logit sensitivity) of 0.82, Tau^2 (logit specificity) of 2.79, MOR (sensitivity) of 2.37, MOR (specificity) of 4.91, and 95 % prediction ellipse area of 0.214. Threshold effect was not detected in studies assessing dentine caries (rho = 0.427; $p = 0.193$) or studies assessing any caries depth (rho = 0.006; $p = 1.000$). Publication bias was not detected in studies assessing dentine caries, where no asymmetry was observed in Deeks' funnel plot ($p = 0.883$). However, the results of Deeks' test ($p = 0.015$) indicated the presence of publication bias for studies assessing any caries depth (Table 4; Fig. 6).

Results of I^2 test (DOR) of the studies assessing diagnostic accuracy of visually detecting caries in clinical photographs for the subgroup of dentition types (using dentine caries data) were 84 % and 94 % for permanent and primary dentition, respectively. For the subgroup of dentition types (using data from any caries depth data), I^2(DOR) were scored 92 % and 90 % for permanent and primary dentition, respectively. The subgroup analysis on the effect of the types of photographic technology utilized resulted in I^2(DOR) of 89 % and 95 % for clinical photographs taken using smartphones, and IOC respectively. The subgroup analysis on the influence of the professional background of the photographer showed I^2(DOR) of 92 % and 62 % for clinical photographs taken by dental professional and layperson respectively (Table 3).

Meta-regression has not addressed the existing heterogeneity observed for studies reporting the diagnostic accuracy of visually detecting caries in clinical photographs, with the exception of applying the covariate of diagnostic thresholds, resulting in an R^2 of 9 %. Results of meta-regression were obtained by applying the following covariates: the caries depth (Tau^2: 1.651; Standard error: 0.560; $p = 0.131$), dentition (using dentine caries threshold data) (Tau^2: 1.234; Standard error: 0.699; $p = 0.597$), dentition (using data from any caries depth) (Tau^2: 4.327; Standard error: 3.024; $p = 0.898$), photographic technology (Tau^2: 1.757; Standard error: 1.015; $p = 0.913$), and the professional background of the photographer (Tau^2: 2.623; Standard error: 1.396; $p = 0.597$) (Table 5).

4. Discussion

This systematic review and meta-analysis assessed eighteen clinical studies which utilized visual detection of dental caries through clinical photographs, comparing them with visual clinical intraoral examination. In this study, the key accuracy parameters presented were sensitivity, specificity, and DOR. Sensitivity represents the proportion of caries that are correctly identified, while specificity represents the proportion of sound tooth sites that are correctly identified. DOR measures the overall effectiveness of visual assessment of clinical photographs. Despite the observed heterogeneity in the results, the utilization of clinical photographs for visual caries detection shows great potential in the detection of dental caries. Specifically, it has exhibited excellent performance in accurately identifying sound tooth structure.

The utilization of diagnostic thresholds is pivotal in defining "carious" and "caries-free" statuses within a given population [52]. When employing visual photographic assessment for caries detection focusing solely on the presence or absence of caries, regardless of lesion depth, the highest pooled DOR, AUC, and pAUC values were obtained (Table 2). This outcome is anticipated as a broader spectrum of carious lesions is encompassed within the threshold, thereby increasing the likelihood of detecting true-positive cases. Furthermore, studies assessing caries extending into dentine have demonstrated higher accuracy parameters compared to those limited to enamel (Table 2), as it is more straightforward to photographically identify extensive and prominent lesions. Nevertheless, the test for subgroup differences suggested the absence of statistically significant subgroup effect (Sensitivity $p = 0.061$; Specificity $p = 0.181$; DOR $p = 0.072$). Notably, the comparatively smaller sample size of enamel caries studies may introduce uncertainties in detecting subgroup variations. Significant differences in between-study heterogeneity of sensitivity values among caries depth subgroups were also noted.

When employing visual photographic assessment for caries detection in primary teeth, higher DOR values were observed compared to permanent teeth (Table 3). This finding aligns with a previous report indicating that examiners found it more straightforward to determine caries presence in intra-oral photographs of primary teeth compared to permanent teeth [53]. The difference in statistical significance of sensitivity values using data extracted from studies assessing any caries ($p = 0.044$) and dentine caries ($p = 0.169$) may be attributed to significant unexplained heterogeneity across studies within each subgroup, as indicated by high I^2 indexes and wide 95 % CI intervals (Table 3). This heterogeneity likely contributed to inconsistent sensitivity outcomes within the subgroups (Table 3).

Subgroup analysis indicates that the selection of photographic technology does not significantly impact the diagnostic performance of visual photographic caries detection. As the trend of researching the validity of telehealth tools continues to grow, there is a notable increase in studies focusing on the use of smartphone photographs for visual caries detection, where the sample size for smartphone-based detection is nearly double that of studies using intra-oral cameras (Table 3). While both smartphones and intra-oral cameras exhibit similar levels of sensitivity, specificity, and DOR values (Table 3), these findings challenge prior assertions regarding the inferior image quality and reproducibility associated with intraoral cameras [34,54]. Due to insufficient primary studies, subgroup analysis on DSLR cameras was not feasible. However, previous findings have indicated that both smartphone cameras and DSLR cameras deliver satisfactory image quality and color accuracy for dental intraoral photography [55,56]. It should be noted that the diagnostic accuracy achieved with DSLR cameras remains uncertain.

Enabling laypersons to capture intraoral photographs for diagnostic purposes can address barriers to accessing dental services and streamline the collection of case-relevant information. Meta-analytical findings indicate that visual caries detection using photographs taken by laypersons generally exhibit lower DOR values compared to those by dental professionals, although no statistical significance was detected (Table 3). Subgroup analysis suggests that the photographer's professional background does not significantly alter diagnostic performance (Sensitivity $p = 0.955$; Specificity $p = 0.410$; DOR $p = 0.466$). However, the presence of uneven sample size distribution and unexplained heterogeneity may introduce uncertainties to the conclusions drawn from the analysis.

The presence of heterogeneity among included studies, as quantified by the I^2 indexes and 95 % prediction ellipse areas, needs to be considered when interpreting the meta-analytical results. In particular, the analysis indicates that specificity contributes more significantly to the heterogeneity observed than sensitivity. This is attributed to the relatively higher MOR for specificity, ranging from 2.65 to 4.91, compared to that of sensitivity, which falls between 1.17 and 2.37 (Table 4). Only an estimated 9 % of heterogeneity is accounted for by applying the covariate of diagnostic thresholds, while dentition, photographic technology, and professional background of the photographer did not influence the effect size of the included studies (Table 5). This suggests that the effect of potential confounding variables has yet to be addressed in this study, due to insufficient primary studies and study characteristics reporting. The presence of publication bias, as indicated by a positive result ($p = 0.015$) in Deeks' test, suggests that the included studies assessing dentine caries did not constitute a representative sample of the available evidence. Interpretation of a positive result must be done under the impression that it is still uncertain whether publication bias exists in studies evaluating diagnostic accuracies [57].

Regarding methodological heterogeneity, risk of bias and applicability concerns were raised in half of the included studies in relation to patient selection. Some of the included studies utilized non-probability sampling where patients were selected for inclusion due to convenience. This may create an unrealistic caries prevalence and affect the diagnostic effects. Future studies should employ consecutive or random sampling to avoid introducing potential bias. Moreover, researchers should carefully construct and execute the exclusion criteria with discretion to recreate an appropriate spectrum of samples just like those a clinician would encounter in clinic. Caries-like features, such as staining and enamel defects, should not be excluded. Index test domain remains mostly low risk and concern as most studies reported pre-specified thresholds and interpreted the photographic results without knowledge of the reference standard. The reference standard domain was rated unclear risk of bias and applicability concern in all the included studies as there is yet a reference standard that could correctly detect the presence or absence of lesions with high validity and reproducibility in clinical context, except in the case of extracting and examining the target tooth under histological investigations. It is unclear whether calibration-dependent clinical intraoral examinations are likely to correctly classify caries as positive results.

While the result of this review showed promising outcomes, several challenges exist when diagnosing dental caries with visual assessment on clinical photographs. The inherent shortcoming of photography lies in its two-dimensional view of a three-dimensional dentition, which precludes the assessment of tooth surfaces not captured by photographs [58]. While both intraoral photographs and clinical examinations incorporate visual elements, the challenge of diagnosis based on photographs is compounded by the variability in the quality of the images. Inaccurate color reproduction in photographs can impact the interpretation of texture and color, leading to challenges in identifying incipient caries and distinguishing them from darkened enamel defects, as previously reported [42,59]. Moreover, alterations in photographic angulations may also change the perspective of the image, affecting the size of demineralization detected [60]. More importantly, the appearance of reflections from the flash may mask carious lesions, particularly at gingival areas where root caries can be found [61]. Additionally, photographic findings may not necessarily correlate with clinical findings, as photographs do not provide clinically obtained information such as tactile sensation. Other factors such as tooth position, saliva control, and magnification may also influence photographic diagnosis.

The limitations of this review primarily stem from the heterogeneity of the included studies. Despite attempts to address statistical heterogeneity through subgroup analysis and meta-regression, potential confounding factors among the included studies were not adequately addressed. To enhance the quality of future research, researchers are encouraged to utilize study designs that involve random selection of study subjects and tooth sites to mitigate all potential sources of bias. Additionally, insufficient reporting of primary study characteristics hindered the analysis of variations in patient cohorts and study designs, leading to the inability to extract diagnostic thresholds in some studies. Furthermore, limited number of studies and the resulting lack of statistical power in subgroup analysis underscore the need for caution when interpreting the data.

5. Conclusion

Current evidence suggests that visual detection of dental caries through clinical photographs demonstrated clinically acceptable diagnostic accuracy when compared with visual clinical intraoral examination. High specificity values across diagnostic thresholds suggest a high level of accuracy in correctly identifying sound tooth structure.

CRediT authorship contribution statement

Jason Chi-Kit Ku: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Kaijing Mao:** Validation, Methodology, Formal analysis, Data curation. **Feifei Wang:** Writing – review & editing, Validation. **Adriana da Fonte Porto Carreiro:** Writing – review & editing, Validation. **Walter Yu-Hang Lam:** Writing – review & editing, Validation, Supervision, Methodology, 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.2025.105737.

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