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REVIEW

Effectiveness of artificial intelligence-assisted colonoscopy in detecting and diagnosing colorectal tumors: a systematic review and network meta-analysis

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Abstract

Background The emergence of artificial intelligence (AI) has greatly promoted the development of the field of medical image analysis, but the potential benefits of AI-assisted colonoscopy and diagnosis (CADe/CADx) for the detection rate of colorectal adenomas and the histological diagnosis of polyps are still controversial and unknown.

Methods We conducted a search on PubMed, Web of Science, Embase, and Cochrane, and the last search time was August 2024. We collected adenoma detection rate (ADR), polyp detection rate (PDR), and sessile serrated lesion detection rate (SSL). Paired analysis and network meta-analysis (NMA) were performed using R Studio. StataSE15.0 software was used for statistical analysis to calculate the sensitivity and specificity of CADx and conventional colonoscopy.

Results We included a total of 64 studies, including 52 RCT studies and 12 clinical studies, with a total of 50,834 patients undergoing colonoscopy. The results showed that different adjuvant interventions had significant differences in the detection rate of adenoma compared with routine colonoscopy ADR [RR = 1.20, 95% CI (1.14, 1.26), $P < 0.001$], and the results were statistically significant. Among different CADe models and advanced optical imaging techniques, ENDOANGEL model-assisted colonoscopy is the most effective method for detecting colorectal adenomas and polyps (97.8%), and Endocuff-AI model-assisted colonoscopy is the most effective method for detecting sessile serrated lesions (94.4%). In the performance study of endoscopists with or without CADX-assisted diagnosis, the optical diagnostic sensitivity of colorectal adenomas was (88% VS 86%), specificity (78% VS 77%), and AUC area (91% VS 89%), and the study results showed no significant differences.

Conclusion ENDOANGEL model-assisted colonoscopy shows the best efficacy on both ADR and PDR, Endocuff-AI model-assisted colonoscopy shows the best performance on SSL, and compared with optical evaluation without CADx, real-time polyp assessment using CADx did not significantly increase the diagnostic sensitivity of neoplastic polyps during colonoscopy.

Keywords Artificial intelligence · Colonoscopy · Adenoma · Detection rate · Diagnosis rate · Systematic review · Mesh meta-analysis

Introduction

According to GLOBOCAN 2022 data, colorectal cancer (CRC) accounts for 1.92 million new cases globally, representing approximately 10.2% of all malignant tumor diagnoses. Furthermore, CRC-related deaths constitute about 9.3% of total cancer deaths, positioning it as the third leading cause of cancer mortality worldwide, following lung and breast cancers. This underscores CRC as a significant global public health concern and a major contributor to the global disease burden [1]. Colorectal polyps, which are elevated lesions that protrude from the intestinal mucosa into the lumen, are classified into four types based on morphology and pathology: adenomatous, inflammatory, hyperplastic, and misshapen polyps [2, 3]. Most CRCs originate from neoplastic polyps, primarily adenomas and sessile serrated lesions (SSLs), with adenomas being the most common precancerous lesions. The "normal mucosa-adenoma-cancer"

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pathway is widely recognized as the primary evolutionary process in CRC development [4], and more than 70% of CRCs develop from adenomas through a series of adenoma-carcinoma gene sequence alterations [5]. Therefore, improving the screening and early detection of colorectal polyps is crucial for reducing the risk of CRC, which has become an increasing focus of public health efforts. A study by Corley et al. [6] found a strong association between ADR and cancer, with a 3.0% reduction in cancer risk and a 5% reduction in colorectal cancer mortality for every 1.0% increase in ADR. Colonoscopy, the gold standard and most widely used method for CRC screening, significantly reduces CRC-related mortality by detecting and removing precancerous polyps. One study demonstrated that colonoscopy screening lowers the risk of death from CRC by 67% [7]. However, there is considerable variability in colonoscopy outcomes based on the qualifications of the endoscopist. These variations are generally classified into two categories: cognitive, which pertains to lesions that are overlooked or not identified, and technical, which relates to issues with insertion or withdrawal techniques. This variability contributes to a significant rate of missed or misdiagnosed polyps, with approximately 26% of adenomas and 27% of serrated lesions being overlooked during screenings [8]. Endoscopists typically remove all detected polyps during colonoscopy, including non-neoplastic inflammatory and hyperplastic polyps, which are then sent for pathological evaluation. This practice can result in unnecessary costs, time consumption, and potential adverse events. To address these limitations, various techniques have been developed, such as water exchange [9], a second examination of the right colon [10], and the use of distal attachments [11] to enhance ADR; however, the effectiveness of these methods is operator-dependent and varies across different clinical settings.

Advances in machine learning and deep learning have led to the development of various AI software, particularly aimed at enhancing polyp detection in endoscopy. A meta-analysis by Hassan [12] demonstrated a significant improvement in ADR for the CADe group compared to the control group (36.6% vs. 25.2%, $P < 0.01$). While CADe has been extensively studied, its most notable impact has been on the detection of small polyps, which typically exhibit low malignant potential. The removal of these polyps for histological evaluation can result in increased healthcare costs. To address this challenge, CADx systems have been developed to enhance the accuracy and reliability of optical diagnoses made by endoscopists. Studies have shown that AI can accurately identify conventional adenomas, serrated adenomas, and hyperplastic polyps with a high degree of confidence. Both computer-aided detection and computer-aided diagnosis meet the target values recommended by the American Society for Gastrointestinal Endoscopy (ASGE) and the American College of Gastroenterology (ACG) [13], with over 10 CADe and CADx devices currently available worldwide. However, their real-world clinical outcomes remain a matter of debate. This study aimed to evaluate whether AI-assisted colonoscopy offers greater benefits compared to standard colonoscopy and advanced imaging techniques through a network meta-analysis. Furthermore, the study sought to compare the advantages and disadvantages of various CADe devices in adenoma detection and to calculate the sensitivity and specificity of CADx and conventional colonoscopy using diagnostic models. The overarching goal was to assess the effectiveness and practical value of CADe and CADx in assisted colonoscopy for polyp detection and diagnosis, thereby providing clinicians with evidence-based guidance for therapeutic decision-making.

Methods

Study design

The protocol has been registered in the International Prospective Register of Systematic Reviews database (PROSPERO:CRD42024587615).

Search strategy

Two researchers searched independently using PubMed, Embase, Cochrane Library, and Web of Science databases. Terms used in queries include colorectal cancer, colorectal cancer, CADe, CADx, computer-aided diagnosis, artificial intelligence, eagle-eye, GI Genius, Endoangel, Henan Tongyu, EndoScreener, self-developed, CAD EYE, SKOUT device EndoVigilant, convolutional neural network, DenceNet-169, ENDOANGEL-CPS, EW10-EC02, magnifying narrow-band imaging, M-NBI, artificial intelligence-based polyp histology prediction, AIPHP, narrow-band imaging international colorectal endoscopic classification, NICE, high definition white-light endoscopy, chromoendoscopy, FUSE, G-Eye, and mucosal visualization systems. Search fields include subject terms, titles, and abstracts, and there are no language or time restrictions on search strategies. The search was conducted from January 2000 to August 2024, in accordance with the Preferred Reporting Project for Systematic Review and Meta-Analysis (PRISMA) guidelines [14].

Inclusion and exclusion criteria

Inclusion criteria:

① The subjects were patients undergoing colonoscopy;
② The study types were randomized controlled trial and clinical controlled trial;

③ The subjects included CADe-assisted colonoscopy, CADx-assisted colonoscopy, advanced optical imaging technology, and routine colonoscopy;
④ Chinese and English literature;

Exclusion criteria:

① The intervention method is not consistent, the study disease is not appropriate, the data is missing or cannot be used for statistical analysis; repeated publication;
② Randomized controlled trials evaluating colorectal cancer surveillance in patients with inflammatory bowel disease or hereditary polyposis syndromes;
③ In vitro experiments, animal experiments, meta-analyses, non-comparative studies, reviews, letters, guidelines, case reports, etc.

Literature screening and data extraction

The retrieved literature was imported into the bibliographic management software EndNote, and data from each eligible study were independently extracted using standardized forms. In duplicate, two researchers independently extracted relevant information, including study objectives, results, and follow-up data, using standardized data extraction tables. The extracted data were cross-checked, and any discrepancies were resolved through discussion.

For each study, the following information was collected: (1) study characteristics, including the first author, country, year of publication, study type, and trial protocol; (2) patient baseline data, including the intervention method, number of patients, and inclusion criteria; and (3) results. For randomized controlled trials (RCTs), we extracted the adenoma detection rate (ADR), defined as the proportion of individuals who underwent complete colonoscopy with at least one adenoma detected, as well as the polyp detection rate (PDR) and serrated sessile lesions (SSL). For randomized series colonoscopy trials, only data from the first colonoscopy were used to avoid carryover effects. For clinical control studies, true positives, false positives, true negatives, and false negatives were extracted.

Risk of bias assessments

For the included RCT studies, two researchers strictly followed the Cochrane bias risk assessment tool to assess the risk of bias in the included literature and used Review Manager 5.4 for analysis: There were seven items, including random assignment, assignment hiding, subject and implementer blind intervention, result blind evaluation, result data integrity, selection to report study results, and other bias. Each item was assessed as "low risk," "unknown risk," and "high risk" for bias risk. For controlled clinical studies, QUADAS-2 (Quality Assessment of Diagnostic Accuracy) was used to assess the risk of bias in each study. GRADEPro is used for evidence grade evaluation. If there is a big difference between the two assessments or if it affects the inclusion of the study in the final analysis, consult a third-party expert to solve the problem.

Statistical analysis

All statistical analyses were conducted using Review Manager 5.4, StataSE 15.0, and R software (version 4.2.2). StataSE 15.0 was employed for statistical analysis, with combined relative risk (RR) and 95% confidence intervals (95% CI) calculated. A P-value of less than 0.05 was considered statistically significant. Sensitivity, specificity, 95% CI, positive likelihood ratio (PLR), negative likelihood ratio (NLR), and diagnostic odds ratio (DOR) were calculated for CADx-assisted endoscopic diagnosis and conventional endoscopy. Additionally, the area under the receiver operating characteristic (AUC) curve was plotted. For the network meta-analysis, a Bayesian model was developed using the gemtc package in R Studio, generating a probability plot and performing probability ranking. The RR and 95% CI were calculated for binary variables, while the weighted mean difference (WMD) and 95% CI were computed for continuous variables. If a closed loop formed among interventions, an inconsistency test was conducted to evaluate the agreement between direct and indirect comparisons, using node analysis. If $P > 0.05$, no significant difference was indicated. The SUCRA (Surface Under the Cumulative Ranking) value for each method was calculated to estimate the overall ranking of treatments, with interventions ranked according to their SUCRA values.

Results

Literature search results

In the initial literature search, a total of 14,672 articles were searched, and 1126 articles were searched only after RCT and controlled clinical trials, and 246 duplicate and unqualified studies were excluded. After reading the title and abstract of the article, 652 studies were excluded according to the exclusion criteria, and 228 studies were preliminarily included. We then read the full text and excluded 163 studies that did not meet the inclusion criteria. Finally, 52 RCT studies were included in the mesh meta-analysis, and 12 controlled clinical studies were included in the diagnostic meta-analysis. The literature screening process and results are shown in Fig. 1.

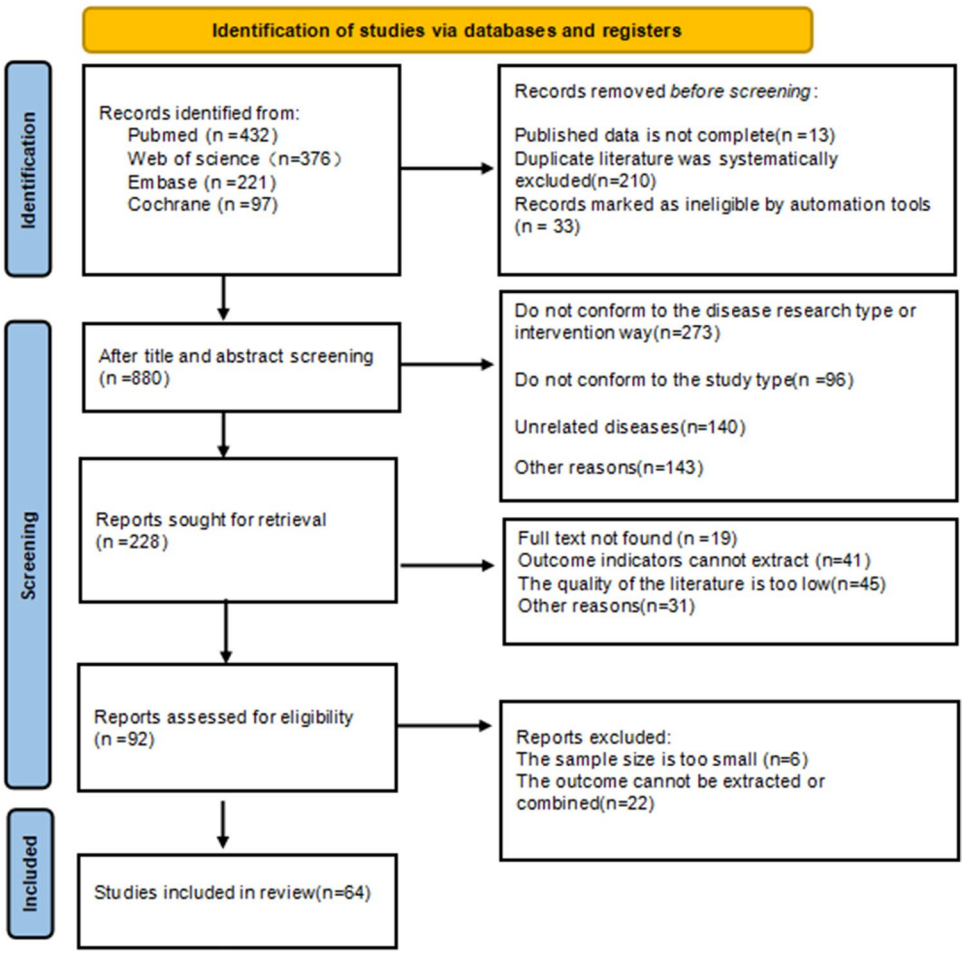

Fig. 1 Schematic diagram of literature search criteria and including studies in meta-analyses

Basic characteristics of the included studies

The 52 studies included were RCT studies with a total of 46,177 patients undergoing colonoscopy. The 12 controlled clinical studies included a total of 4657 patients who underwent colonoscopy. Study characteristics, patient baseline, and study results of the included studies are shown in Tables 1 and 2.

The quality assessment of the included studies

Fifty-two RCT studies were evaluated using the Cochrane Bias Risk Tool (Review Manager 5.4 tool). Forty-one studies reported specific methods of generating random sequences, rated as "low risk," and the remaining 11 studies, none of which mentioned random methods, rated as "high risk." All 48 studies mentioned the blind method (37 double-blind and 11 single-blind); 52 studies did not describe the content related to allocation hiding, which was rated as "unclear risk," and four studies did not mention the blind method, so it was evaluated as "high risk." All 52 studies reported outcome measures of anticipation, rated as "low risk." None of the 52 studies detailed other biases and was rated as "low risk." QUADAS-2 was used to evaluate the evidence level of 13 controlled clinical studies, among which 12 literatures had a low risk of case selection bias, and one [57] did not mention whether patients were continuously included, so it was evaluated as high risk. Most of the literatures did not mention whether threshold values were used or whether blind interpretation of the gold standard was used. Therefore, for the majority of literatures, we assessed that the overall risk of bias was low in 13 literatures for the sake of unclear. The results of literature quality evaluation are shown in Figs. 2 and 3.

Certainty of evidence

GRADEpro was used in this study to assess the certainty of the evidence. Table 3 shows that ADR is high-quality evidence, PDR and SSL are medium-quality evidence. The highly varied interventions and the high heterogeneity, low methodological quality, and high risk of bias in some outcomes may have contributed to the low quality of evidence.

Table 1 Clinical and demographic characteristics of the studies included in the meta-analysis

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Daisuke Yamaguchi [15]	Japan	2024	RCT	Multicenter	CADe	CAD EYE (Fujifilm)	Conventional colonoscopy	113	118	The colonoscopy examinations were performed either because of a positive fecal immunochemical test or for surveillance after colonic polypectomy	2021–2022	ADR, PDR, AMR
Johanna Schöler [16]	Sweden	2024	RCT	Multicenter	CADe	CAD EYE (Fujifilm)	Conventional colonoscopy	98	120	Patients with a history of inflammatory bowel disease (IBD), contraindication for polypectomy or known polyps were excluded. Incomplete examinations due to factors such as obstructive cancer, technical issues or inadequate bowel preparation, as well as cases where the Boston Bowel Preparation Scale (BBPS) 16 < 2 in 1 segment or a total BBPS < 6, were excluded from the primary analysis	2020–2022	ADR, PDR, SSL
Johanna Schöler2	Sweden	2024	RCT	Multicenter	CADe	GI Genius	Conventional colonoscopy	24	120		2020–2022	ADR, PDR, SSL
Kasenee Tiankanon [17]	Thailand	2024	RCT	Multicenter	CADe	SD-CADe	Conventional colonoscopy	400	400	Participants with known colorectal cancer history, inflammatory bowel diseases, familial polyposis syndrome, and patients with prior colonic resection were excluded from the study	2022–2023	ADR
Kasenee Tiankanon2	Thailand	2024	RCT	Multicenter	CADe	CM-CADe	Conventional colonoscopy	400	400		2022–2023	ADR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Kazuya Miyaguchi [18]	Japan	2024	RCT	Monocentric	CADe	CAD EYE (Fujifilm) + LCI	LCI	400	400	The exclusion criteria were patients who underwent colonoscopy without bowel preparation, and those with intestinal obstruction, stenosis, fistula, a history of colorectal surgery, active inflammatory bowel disease, diverticulitis, or active or suspected colorectal bleeding	2022–2023	ADR
Louis H. S [19]	China	2024	RCT	Monocentric	CADe	ENDO-AID [OIP-1]	Conventional colonoscopy	386	380	Subjects were excluded if they had contraindications to colonoscopy or polypectomy, known colorectal lesions for staged procedures, previous colonic resection, personal history of CRC/polyposis syndrome/inflammatory bowel disease, advanced comorbid conditions (American Society of Anesthesiologists grade 4), or pregnancy	2021–2022	ADR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Madhav Desai [20]	Sweden	2024	RCT	Multicenter	CADe	EW10-EC02	Conventional colonoscopy	509	522	Excluded if they had a history of colon resection, inflammatory bowel disease, familial adenomatous polyposis, and severe comorbidity, including endstage cardiovascular/pulmonary/liver/renal disease, were pregnant during the study period, and were not able to or refuse to give informed consent	NA	ADR, PDR, SSL
Oswaldo Ortiz [21]	Spain	2024	RCT	Multicenter	CADe	GI Genius	HDWL	214	216	Exclusion criteria were history of total colectomy, concomitant inflammatory bowel disease, inability or refusal to sign the informed consent, colonoscopy within the past 12 months, inadequate bowel preparation, incomplete procedure, and PMS2 mutation	2021–2023	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Thomas Ka-Luen Lui [22]	China	2024	RCT	Multicenter	CADe	Endocuff-AI	Conventional colonoscopy	230	214	Exclusion criteria included pregnant women, inability to provide written informed consent, prior colorectal resection, personal history of CRC, inflammatory bowel disease, familial adenomatous polyposis, PeutzJeghers syndrome, or other polyposis syndromes	2022–2023	ADR, PDR, SSL
Thomas Ka-Luen Lui2	China	2024	RCT	Multicenter	CADe	AI	Conventional colonoscopy	238	214		2022–2023	ADR, PDR, SSL
Antonio Z [23]	USA	2023	RCT	Monocentric	CADe	ENDO-AID [OIP-1]	Conventional colonoscopy	155	157	Excluded colon resection, treatment with anticoagulants or antiplatelet agents that may preclude polyp resection, a recent good-quality colonoscopy (<6 months) (i.e., scheduled for endoscopic therapy), inflammatory bowel disease, incomplete colonoscopy, and inadequate preparation assessed by the Boston Bowel Preparation Scale (BBPS)0.15	2021–2022	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Carolina Mangas-Sanjuan [24]	Spanish	2023	RCT	Multicenter	CADe	GI Genius	Conventional colonoscopy	1610	1603	Excluded if they had a personal history of CRC, inflammatory bowel disease, colorectal surgery, terminal illness or severe disease, familial CRC or family history of inherited CRC syndrome, or lack of informed written consent	2021–2022	ADR, PDR, SSL
Hirotaka Nakashima [25]	Japan	2023	RCT	Monocentric	CADe	CAD EYE (Fujifilm)	HDWL	207	208	Exclusion criteria included patients who (1) underwent colorectal surgery and (2) had an inflammatory bowel disease	2021–2022	ADR
Hong Xu [26]	China	2023	RCT	Multicenter	CADe	Eagle-Eye	Conventional colonoscopy	1519	1540	Patients were excluded from the study if they were unable to provide informed consent, had contraindications for endoscopy, overt symptoms suggestive of colorectal disorders, history of inflammatory bowel disease, CRC, polyposis syndrome, prior colorectal surgery, or colonoscopy within 10 years	2019–2021	ADR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Jeremy R. Glissen Brown [27]	USA	2023	RCT	Multicenter	CADe	EndoScreener	HDWL	113	110	Incomplete colonoscopies (those where endoscopists did not successfully intubate the cecum due to technical difficulties or poor bowel preparation) and patients found to have a Boston Bowel Preparation Scale (BPPS) score of 0 to 1 in any of three segments were excluded from the primary analysis	2019–2020	ADR, PDR, SSL
Mike T. Wei [28]	USA	2023	RCT	Multicenter	CADe	EndoVigilant	Conventional colonoscopy	387	382	Exclusion criteria were patients with history of inflammatory bowel disease (ulcerative colitis, Crohn's disease), known or suspected polyposis or hereditary colon cancer syndrome (such as familial adenomatous polyposis, hereditary non-polyposis colon cancer)	NA	ADR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Satimai Aniwan [29]	Thailand	2023	RCT	Multicenter	CADe	CAD EYE; Fujifilm	Conventional colonoscopy	312	310	Exclusion criteria were patients with inflammatory bowel diseases, familial polyposis syndrome, history of CRC, postpolypectomy surveillance, prior colonic resection, and prior pelvic radiation	2020–2022	ADR
Satimai Aniwan2	Thailand	2023	RCT	Multicenter	CADe	CADe + EAC	Conventional colonoscopy	308	310			
Aasma Shaukat [30]	USA	2022	RCT	Multicenter	CADe	AI	Conventional colonoscopy	682	677	Excluded from this study if they had a diagnostic indication for their procedure, a history of inflammatory bowel disease, or familial adenomatous polyposis	2021	ADR, PDR, SSL
Ahmir Ahmad [31]	UK	2022	RCT	Multicenter	CADe	GI Genius	Conventional colonoscopy	308	306	Exclusion criteria were patients with a risk profile (due to family history or other reasons), whose follow-up was conducted outside the BCSP, and those who did not give consent to the study	2020–2021	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Emanuele Rondonotti [32]	Italy	2022	RCT	Multicenter	CADe	CAD EYE (Fujifilm)	HDWL	405	395	Individuals were excluded from the study if they were not eligible for the screening program (i.e., colonoscopy performed in the previous 5 years, personal history of CRC, colonic adenomas, inflammatory bowel disease, severe comorbidity)	2020–2021	ADR, SSL
Liwen Yao [33]	China	2022	RCT	Monocentric	CADe	YOLO V3	Conventional colonoscopy	268	271	Patients with known contraindications to biopsy, bowel obstruction or perforation, or those who were pregnant or lactating, suffering from polyposis syndromes or who had a history of inflammatory bowel disease, CRC, or colorectal surgery were excluded	2020	ADR, PDR, SSL
Alessandro Repici [34]	Italy	2021	RCT	Multicenter	CADe	GI Genius	HDWL	330	330	Patients were excluded in case of personal history of CRC, or IBD, previous colonic resection, antithrombotic therapy precluding polyp resection and lack of informed written consent	2020	ADR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Lei Xu [35]	China	2021	RCT	Multicenter	CADe	AI	Conventional colonoscopy	1177	1175	Exclusion criteria include: patients who were unwilling to participate in the study; emergency colonoscopy; colonoscopic polypectomy; patients with a history of colorectal polyps; patients with a history of colorectal resection	2018–2019	PDR
Shunsuke Kamba [36]	Japan	2021	RCT	Multicenter	CADe	YOLO V3	Conventional colonoscopy	178	177	Excluded: known inflammatory bowel disease or stenosis of the large intestine, known familial polyposis, known colon polyps or advanced cancer, history of post-colorectal surgery (excluding appendectomy or rectal surgery), blood coagulation disorders, serious organ failure, pregnancy, and ineligible for registration as judged by the operator	2019–2020	ADR, PDR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Wen-Na Liu [37]	China	2020	RCT	Monocentric	CADe	AI	Conventional colonoscopy	508	518	Exclusion criteria: any participant with inflammatory bowel disease, history of CRC surgery, history of radiotherapy and/or chemotherapy, and biopsy contraindications	2018–2019	ADR, PDR
Pu Wang [38]	China	2020	RCT	Monocentric	CADe	EndoScreener	Conventional colonoscopy	184	185	Excluded patients with a history ofinflammatory bowel disease, colorectal cancer, colorectal surgery, or contraindication for biopsy	2019	ADR, PDR
Pu Wang2 [39]	China	2020	RCT	Monocentric	CADe	EndoScreener	Conventional colonoscopy	484	478	Excluded patients with a history of inflammatory bowel disease, colorectal cancer, or colorectal surgery or who had a contraindication for biopsy (e.g., use of anticoagulants)	2018–2019	ADR, PDR
Peixi Liu [40]	China	2020	RCT	Monocentric	CADe	EndoScreener	Conventional colonoscopy	393	397	Excluded patients with a history of inflammatory bowel disease (IBD), CRC, any polyposis syndromes, colorectal surgery and patients with a contraindication for biopsy	2018–2019	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Jing-Ran Su [41]	China	2020	RCT	Monocentric	CADe	AQCS	Conventional colonoscopy	308	315	Exclusion criteria were (1) patients with contraindications to colonoscopy examination; (2) patients with a history of inflammatory bowel disease (IBD), patients with CRC or colorectal surgery; (3) patients with prior failed colonoscopy or who are highly suspicious for polyposis syndromes, IBD, or typical advanced CRC	2018–2019	ADR, PDR
Dexin Gong [42]	China	2020	RCT	Monocentric	CADe	ENDOANGEL	Conventional colonoscopy	355	349	Exclusion criteria were absolute contraindications to colonoscopy examination, known polyposis syndromes, and a history of inflammatory bowel disease, colorectal cancer, or colorectal surgery	2019	ADR, PDR
Alessandro Repici2 [43]	USA	2020	RCT	Multicenter	CADe	GI Genius	HDWL	341	344	Excluded in case of personal history of CRC, or IBD, previous colonic resection, antithrombotic therapy precluding polyp resection, and lack of informed written consent	2019	ADR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Pu Wang3 [44]	China	2019	RCT	Monocentric	CADe	EndoScreener	Conventional colonoscopy	522	536	Excluded patients with a history of inflammatory bowel disease, colorectal cancer, or colorectal surgery or who had a contraindication for biopsy (e.g., use of anticoagulants)	2017–2018	ADR, PDR
Mohammed Sherif Naguib [45]	Egypt	2024	RCT	Monocentric	Advanced imaging	Endocuff	Conventional colonoscopy	214	214	Patients who have contraindications to colonoscopy (suspected perforated viscus and bleeding diathesis, platelet dysfunction or hemophilia), patients with known colonic disease	2018–2020	ADR
Chang-wei DUAN [46]	China	2024	RCT	Multicenter	Advanced imaging	HDWL	Conventional colonoscopy	161	281	Exclusion older than 75 years old; colonoscopy or bowel preparation intolerance, such as severe cardiopulmonary dysfunction; patients with serious comorbid diseases	2017–2020	ADR, SSL
Chang-wei DUAN2	China	2024	RCT	Multicenter	Advanced imaging	NBI	Conventional colonoscopy	154	281		2017–2020	ADR, SSL
Jun Li [47]	China	2023	RCT	Multicenter	Advanced imaging	LCI	WLI	441	443	Exclusion criteria were patients in poor condition who could not tolerate or cooperate with the examination; patients with a history of inflammatory bowel disease, polyposis syndrome, or CRC	2020–2021	ADR, PDR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Giulio Antonelli [48]	Italy	2023	RCT	Multicenter	Advanced imaging	TXI	WLI	375	372	Excluded if they had a history of CRC, inflammatory bowel disease, or previous colonic resection, received antithrombotic therapy precluding polyp resection, or did not provide informed written consent	2021–2022	ADR, SSL
Katharina Zimmermann [49]	Germany	2023	RCT	Multicenter	Advanced imaging	Endocuff	Conventional colonoscopy	700	716	Excluded if they had symptoms that could indicate colonic disease, had a colonic bleed, or had known colon disease (carcinoma, polyps for ablation, inflammatory bowel disease, and stenosis)	2017–2020	ADR, SSL
Sho Suzuki [50]	Japan	2023	RCT	Multicenter	Advanced imaging	LCI	WLI	1402	1428	Exclusion criteria were as follows: history of colorectal surgery, inflammatory bowel disease, hereditary polyposis syndrome, or nonhereditary polyposis syndrome; hereditary nonpolyposis CRC; having a colorectal adenoma, polyps, or cancer on pretrial colonoscopy	2020–2022	ADR, PDR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Shu Tanaka [51]	Japan	2023	RCT	Monocentric	Advanced imaging	LCI	WLI	305	289	Exclusion criteria included polyposis syndromes, inflammatory bowel disease, previous total or partial colonic resection, history of colonoscopy during the previous 2 years, possible colonic stricture, and acute abdominal pain or severe inflammation	2018–2019	ADR, PDR
Sukit Pattarajierapan [52]	Thailand	2023	RCT	Monocentric	Advanced imaging	TXI + Endocuff	TXI	189	192	Excluded patients with a CRC history, previous colonic resection, previous colonoscopy, known colonic stricture, inflammatory bowel disease, familial polyposis syndrome, or those who did not consent to participate in the study	2022	ADR
Seung Wook Hong [53]	South Korea	2022	RCT	Monocentric	Advanced imaging	WingCap	Conventional colonoscopy	269	259	Excluded patients who were scheduled for therapeutic colonoscopy for colonic neoplasm or those who had undergone colorectal surgery for cancer or for other reasons	2022	ADR, PDR, SSL

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Madhav Desai [54]	USA	2022	RCT	Multicenter	Advanced imaging	HDWLE	Endocuff	384	379	Excluded prior history of colorectal cancer, history of inflammatory bowel disease, prior surgical resection of any part of the colon, concurrent use of antiplatelet agents or anticoagulants that precludes the removal of polyps	2022	ADR, SSL
Claudia Jaensch [55]	Denmark	2022	RCT	Monocentric	Advanced imaging	Endocuff	Conventional colonoscopy	588	590	Excluded prior history of colorectal cancer, history of inflammatory bowel disease, prior surgical resection of any part of the colon, concurrent use of antiplatelet agents or anticoagulants that precludes the removal of polyps	2017–2018	ADR, PDR
Satimai Aniwan [56]	Thailand	2021	RCT	Monocentric	Advanced imaging	Endocuff	LCI	250	250	Excluded participants with a history of CRC, inflammatory bowel diseases, familial polyposis syndrome, colonic resection, or a positive fecal occult blood test	2019–2020	ADR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Manuel Zorzi [57]	Italy	2021	RCT	Multicenter	Advanced imaging	Endocuff	Conventional colonoscopy	908	905	Patients were excluded from the current study if they had a personal history of CRC, or inflammatory bowel disease, previous colonic resection, antithrombotic therapy precluding polyp resection, or were unable to provide written informed consent	NA	ADR, SSL
Kazuya Miyaguchi [58]	Japan	2021	RCT	Multicenter	Advanced imaging	WLI	LCI	501	494	Patients undergoing colonoscopy without pretreatment and those with intestinal obstruction, stenosis, fistula, a history of colorectal surgery, active inflammatory bowel disease, diverticulitis, and active or suspected colorectal bleeding were excluded	2018–2019	ADR, SSL
Issei Hasegawa [59]	Japan	2021	RCT	Monocentric	Advanced imaging	WLI	LCI	349	351	Additionally, we excluded patients with a history of multiple polyps (> 10), previous colorectal resection, nonstandardized preparation methods, inability to provide informed consent, or refusal of the procedure	2017–2020	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Britt B S L Houwen [60]	Italy	2021	RCT	Multicenter	Advanced imaging	LCI	HDWLE	160	172	Exclusion criteria included surveillance colonoscopy within 1 year of the current examination, colonoscopy planned for the evaluation of symptoms, total proctocolectomy, known colonic neoplasia (referred patients),or a concurrent diagnosis of (serrated) polyposis syndrome or inflammatory bowel disease	2018–2020	ADR, PDR, SSL
Silvia Paggi [61]	Italy	2020	RCT	Multicenter	Advanced imaging	LCI	WLI	326	323	Excluded prior history of colorectal cancer, history of inflammatory bowel disease, prior surgical resection of any part of the colon, concurrent use of antiplatelet agents or anticoagulants that precludes the removal of polyps	2018–2019	ADR, PDR
Barbara Dorottya [62]	Hungary	2020	RCT	Monocentric	Advanced imaging	LCI	HDWLE	552	726	Exclusion criteria were: inadequate bowel preparation: Boston Bowel Preparation Score (BBPS) to apply HQ electronic chromoendoscopy with LCI technology (under totally 6 points or 2 points in any segment)	2016–2018	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
David Karsenti [63]	France	2019	RCT	Monocentric	Advanced imaging	Endocuff	Conventional colonoscopy	1026	1032	Exclusion criteria were: patients scheduled for partial colonoscopy or interventional colonoscopy (for known polyp resection, stent insertion, stenosis dilation or hemostasis), patients referred for polyp resection, previous colonic surgery, stenosis, recent acute diverticulitis, inflammatory bowel disease, polyposis syndrome, pregnancy, hemostasis disorders and inability to give informed consent	2017–2018	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Wee Sing Ngu [64]	UK	2019	RCT	Multicenter	Advanced imaging	Endocuff	Conventional colonoscopy	888	884	Patients were excluded if there was a pre-endoscopy suspicion of large bowel obstruction; known colon cancer or polyposis syndromes; known colonic stricture; known severe diverticular segment; known active colitis; on anticoagulants which had not been stopped preprocedure (meaning polypectomy might not be undertaken); if pregnant or attending for a therapeutic procedure or assessment of a known lesion	2014–2016	ADR
Wai K. Leung [65]	China	2019	RCT	Monocentric	Advanced imaging	LCI	NBI	136	136	Patients were excluded if they were unable to provide informed consent, had undergone previous colorectal resection, had a personal history of colorectal cancer, inflammatory bowel disease, familial adenomatous polyposis, Peutz-Jeghers syndrome, or other hereditary polyposis syndromes	2017–2018	ADR, PDR

Table 1 (continued)

First author	Author states	Year	Research type	Centers	System	Means of intervention		Case load		Exclusion criteria	Follow-up time	Included indicators
						Experimental group	Control group	Experimental group	Control group			
Rivero-Sánchez [66]	Spain	2019	RCT	Multicenter	Advanced imaging	HDWLE	Pancolonic chromoendoscopy	128	128	Excluded patients who were scheduled for therapeutic colonoscopy for colonic neoplasm or those who had undergone colorectal surgery for cancer or for other reasons	2016–2018	ADR, PDR
Haewon Kim [67]	Korea	2019	RCT	Monocentric	Advanced imaging	NBI	HDWLE	58	59	Exclusion criteria included: familial colorectal cancer syndrome, a personal history of colorectal cancer or inflammatory bowel disease, (3) previous colonic resection, and (4) inadequate bowel preparation [Boston Bowel Preparation Scale (BBPS) score < 6]	2015–2017	ADR, PDR

HDWLE high definition white light endoscopy, *LCI* linked color imaging, *NBI* narrow-band imaging, *WLI* white-light imaging, *TXI* texture and color enhancement imaging, *ADR* adenoma detection rate, *PDR* polyp detection rate, *SSL* sessile serrated lesion.

Table 2 Clinical and demographic characteristics of the studies included in the meta-analysis

First author	Author states	Year	Research type	Centers	Endoscopes	CADx system	Follow-up time	Patients	TP		FP		FN		TN	
									CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted
Douglas K. Rex [68]	USA	2024	Prospective	Monocentric	Olympus endoscopes of the CF-H 190 and CF-HQ 1100 series with an Olympus Evis X1 processor were used	GI Genius	2020–2022	1252	1387	1393	473	408	135	129	700	765
Sebastian Baumer [69]	Germany	2024	Prospective	Monocentric	Olympus endoscopes of the CF-H 190 and CF-HQ 1100 series with an Olympus Evis X1 processor were used	GI Genius	2022	115	152	148	30	24	13	17	67	73
Yaxuan Cheng [70]	China	2024	Retrospective	Monocentric	NA	NA	2020–2022	740	294	325	129	76	87	56	328	381
Ejaz Hossain [71]	Japan	2024	Prospective	Monocentric	Olympus (Evis X1) and Fujifilm (Eluxeo 7000) processors	WISE VISION	NA	66	35	58	28	29	11	5	44	43
Shun Kato [72]	Japan	2024	Retrospective	Monocentric	EVIS LUCERA ELITE and EVIS X1 systems CFXZ1200, CF-EZ1500, PCF-H290Z, and CF-H290ECI; Olympus Corporation)	NBI-CAD	2021–2022	385	344	368	23	24	41	17	92	91

Table 2 (continued)

First author	Author states	Year	Research type	Centers	Endoscopes	CADx system	Follow-up time	Patients	TP		FP		FN		TN	
									CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted
James Weiquan [73]	Singapore	2023	Prospective	Multicenter	EC-760Z-V/L and EC-760ZP-V/L colonoscopes, and the ELUXEO VP-7000 processor (Fujifilm, Tokyo, Japan)	ELUXEO 7000	2021–2022	450	287	252	43	32	121	156	210	221
Britt B. S. L. Houwen [74]	USA	2023	Prospective	Multicenter	EVIS EXERA II or III video processors with 190-series Olympus colonoscopes containing NBI (Olympus, Tokyo, Japan)	POLAR	2018–2021	194	315	305	46	51	26	36	36	31
Cesare Hassan [75]	Italy	2022	Prospective	Monocentric	ELUXEO (Fujifilm Co, Tokyo, Japan) or EVIS EXERA III (Olympus Co, Tokyo, Japan) endoscopy systems	GI Genius	2021	162	31	32	6	18	8	7	250	238
Ishita Barua [76]	Norway	2022	Prospective	Multicenter	EVIS LUCERA ELITE, CV-290; Olympus Corp	Endo-BRAIN	2019–2021	525	317	324	90	75	42	35	443	458

Table 2 (continued)

First author	Author states	Year	Research type	Centers	Endoscopes	CADx system	Follow-up time	Patients	TP		FP		FN		TN	
									CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted	CADx-unassisted	CADx-assisted
Emanuele Rondonotti [77]	Italy	2022	Prospective	Multicenter	EC-760ZPV and EC-760RV endoscopes, ELUXEO VP-7000 video processor, and ELUXEO BL-7000 light source; Fujifilm Co	CAD-EYE	2020–2021	389	229	229	38	40	30	30	299	297
Quirine E. W [78]	Netherlands	2021	Prospective	Multicenter	NA	EfficientNet	2019–2020	54	38	38	0	1	7	7	15	14
Yuichi Mori [79]	Japan	2018	Prospective	Monocentric	Evis Lucera Elite CV 290 [Olympus]	Cybernet systems	2017	325	278	167	80	12	40	21	20	9

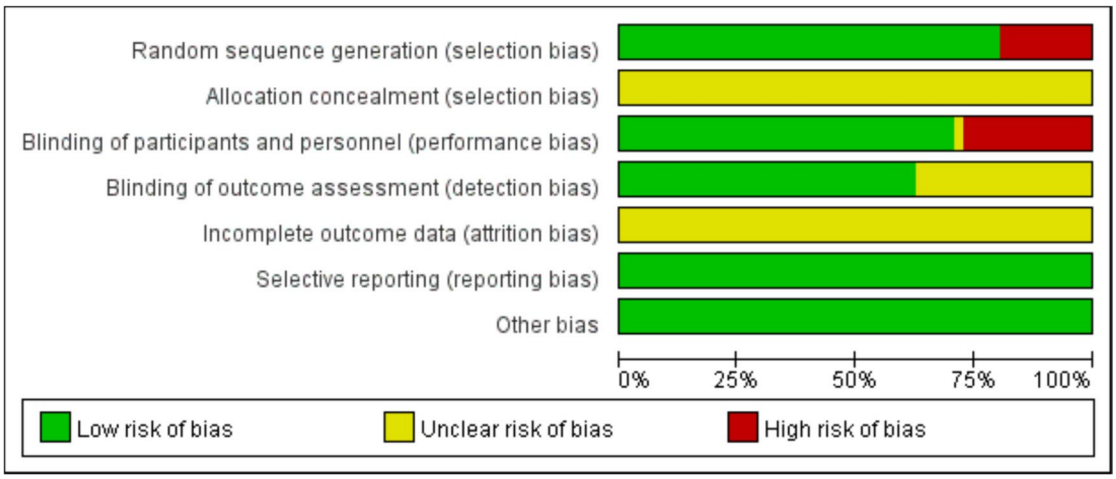

Fig. 2 Risk of bias in included randomized controlled trials

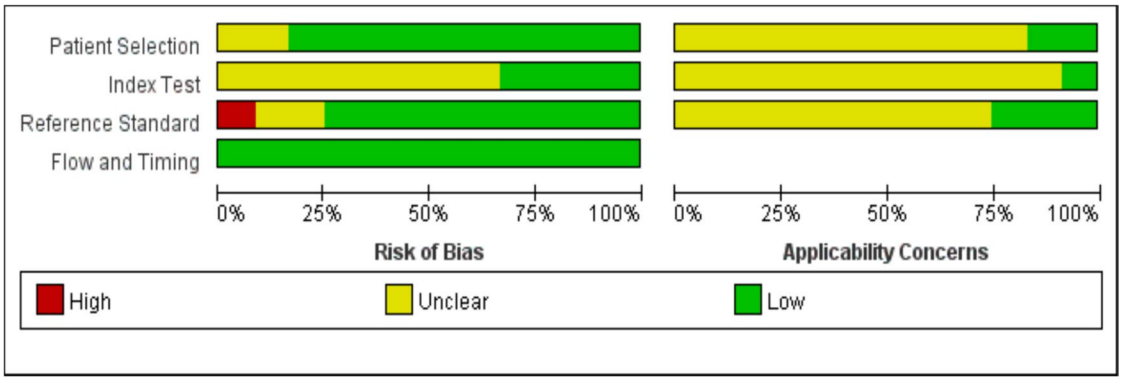

Fig. 3 Risk assessment results of QUADAS-2 scale in the included literature

Meta-analysis results

Thirty studies reported adenoma detection rates of different CADe models and advanced optical imaging technology-assisted colonoscopy versus conventional colonoscopy. Figure 4 shows the hazard ratio forest plots determined in 30 studies. Considering the large heterogeneity among the studies ($P < 0.001$, $I^2 = 76.6\%$), a random effects model was used for meta-analysis. The analysis results showed that the auxiliary detection method had statistical significance in improving the detection rate of colorectal adenoma [RR = 1.20, 95% CI (1.14, 1.26), $P < 0.001$]. Sensitivity analysis showed that the model was robust and reliable, and there was no obvious asymmetry in the shape of the funnel plot. Sensitivity analysis and funnel plot are shown in supplementary Figs. 1 and 2. In summary, we concluded that the source of heterogeneity may be due to the relatively different interventions (AI-assisted and advanced optical imaging techniques).

CADe subgroups and regression analysis

Considering the large heterogeneity of CADe group, we conducted subgroup analysis and univariate and multivariate meta-regression for CADe group. The results of subgroup analysis showed that the type of study, sample size, and whether the series were not the causes of heterogeneity, and the sources of heterogeneity may be related to studies in different countries and regions. Univariate and multivariate meta-regression analyses showed no effect on male prevalence, study sample size, family genetic history, or prevalence in patients undergoing colonoscopy due to positive FIT results ($P > 0.05$) (Tables 4 and 5).

Diagnostic meta results

The combined sensitivity of CAD-X-assisted colonoscopy for predicting polyp histology was 88.0% (95% CI 84.0–91.0%, $I^2 = 97.01$), and the combined specificity

Table 3 Certainty of evidence

Quality assessment							No. of patients		Effect		Quality	Importance
No. of studies	Design	Risk of bias	Inconsistency	Indirectness	Imprecision	Other considerations	Experimental	Control	Relative (95% CI)	Absolute		
ADR												
51	Randomized trials	Serious	No serious inconsistency	No serious indirectness	No serious imprecision	Strong association	10,044/21232 (47.3%)	8668/21513 (40.3%)	OR 1.36 (1.31 to 1.42)	76 more per 1000 (from 66 to 86 more)	⊕⊕⊕⊕ High	Critical
								42.3%		76 more per 1000 (from 67 to 87 more)		
PDR												
33	Randomized trials	Serious	No serious inconsistency	No serious indirectness	No serious imprecision	Strong association	8213/14130 (58.1%)	7238/14343 (50.5%)	OR 1.39 (1.33 to 1.46)	81 more per 1000 (from 71 to 93 more)	⊕⊕⊕⊕ High	Critical
								49.5%		82 more per 1000 (from 71 to 94 more)		
SSL												
22	Randomized trials	Serious	No serious inconsistency	No serious indirectness	No serious imprecision	None	1025/10396 (9.9%)	842/10511 (8%)	OR 1.26 (1.14 to 1.39)	19 more per 1000 (from 10 to 28 more)	⊕⊕⊕ Moderate	Critical
								6.3%		15 more per 1000 (from 8 to 22 more)		

CI confidence interval, *MD* mean difference, *RR* risk ratio

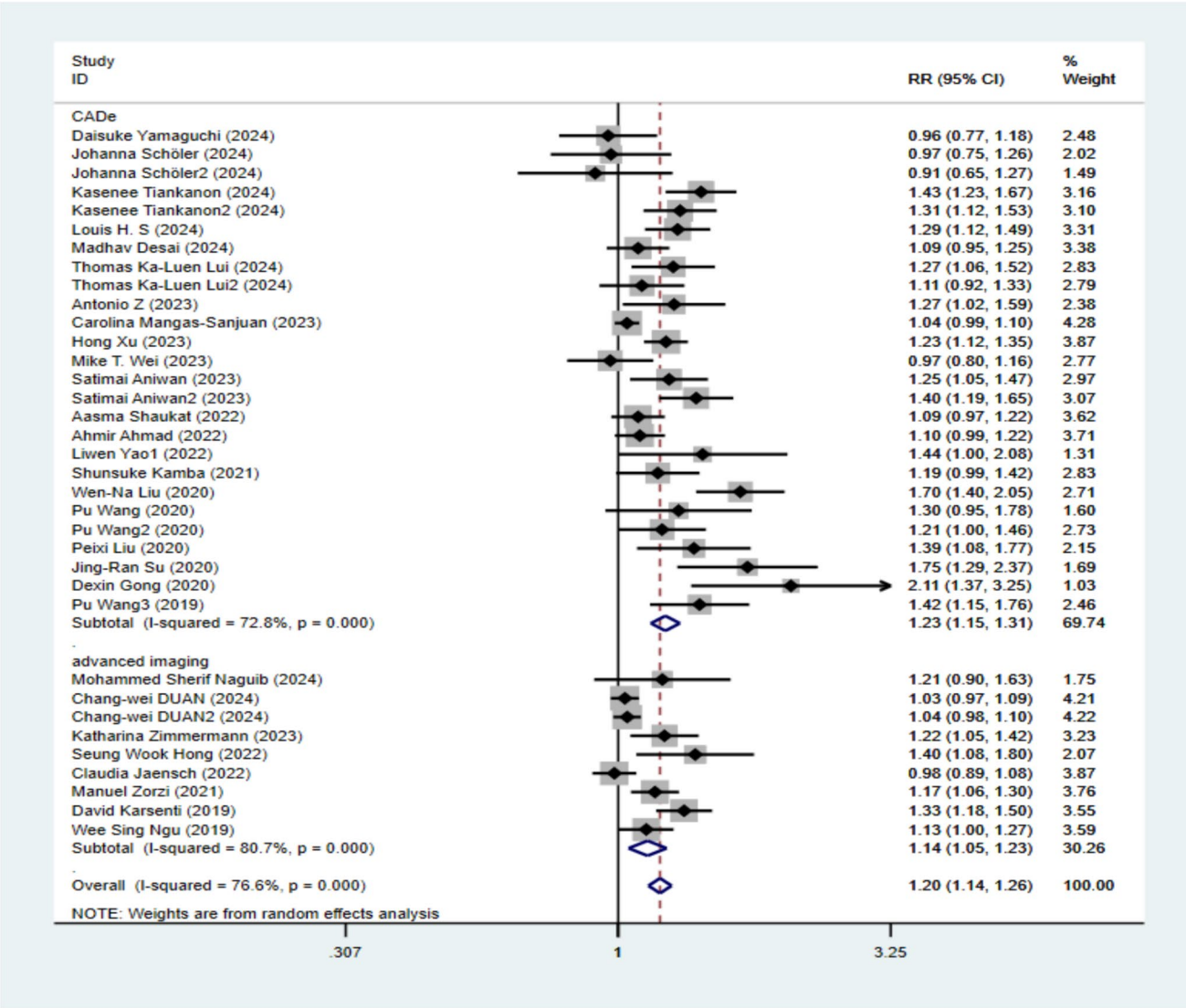

Fig. 4 Forest plot of ADR data

was 78.0% (95% CI 67.0–86.0%, $I^2 = 96.42$), as shown in Fig. 5a. The combined positive likelihood ratio was 3.97 (95% CI 2.66–5.93), and the combined negative likelihood ratio was 0.15 (95% CI 0.11–0.21), as shown in Fig. 5b. The combined AUC is 0.91 (0.88–0.93), as shown in Fig. 7a. The combined sensitivity of diagnosis without CADx was 86.0% (95% CI 82.0–89.0%, $I^2 = 95.58$), and the combined specificity was 77.0% (95% CI 600.0–87.0%, $I^2 = 97.64$), as shown in Fig. 6a. The combined positive likelihood ratio was 3.67 (95% CI 2.07–6.49), and the combined negative likelihood ratio was 0.18 (95% CI 0.14–0.24), as shown in Fig. 6b. The combined AUC is 0.89 (0.86–0.91), as shown in Fig. 7b. The results showed that diagnostic performance with CADx was more accurate than with physicians alone but did not show a significant difference.

Network meta-analysis

ADR

Network evidence graph

ADR was reported in 51 RCTs studies, including 25 interventions (A: conventional colonoscopy, B: CAD EYE (Fujifilm), C: GI Genius, D: SD-CADe, E: CM-CADe, F: ENDO-AID [OIP-1], G: EW10-EC02, H: Endocuff-AI, I: AI, J: Eagle-Eye, K: EndoScreener, L: EndoVigilant, M: CADe + EAC, N: YOLO V3, O: AQCS, P: ENDOANGEL, Q: Endocuff, R: HDWL, S: NBI, T: LCI, U: WLI, V: TXI, W: CNN, X: WingCap, Y: Pancolonic chromoendoscopy). The overall network relationship is centered around the conventional colonoscopy without any additional assistance.

Table 4 Subgroup analysis of sources of heterogeneity

Subgroup	ADR			
	Study	RR (95% CI)	*P* value	I^2
Country				
Japan	2	1.07 (0.87, 1.32)	$P=0.507$	56.3
Sweden	3	1.04 (0.93, 1.17)	$P=0.461$	0
Thailand	4	1.34 (1.24, 1.46)	$P<0.001$	0
China	12	1.35 (1.24, 1.47)	$P<0.001$	50.6
USA	3	1.09 (0.95, 1.24)	$P=0.187$	43
Spanish	1	1.03 (0.98, 1.09)	$P=0.159$	NA
UK	1	1.09 (0.98, 1.22)	$P=0.09$	NA
Research type				
Multicenter	16	1.14 (1.07, 1.22)	$P<0.001$	66.4
monocentric	10	1.41 (1.28, 1.55)	$P<0.001$	36.2
Sample size				
≥500	18	2.00 (1.64, 2.45)	$P<0.001$	79.3
<500	8	1.27 (1.17, 1.37)	$P<0.001$	24.3
Study design				
Routine study	24	1.22 (1.14, 1.31)	$P<0.001$	74.8
Series experiment	2	1.21 (1.03, 1.42)	$P=0.016$	0

The dots represent this intervention measure. The connection between two points with a straight line indicates the existence of a direct comparison. The thickness of the line represents the number of studies included in the research. The evidence network relationship diagram shows that it contains closed loops (Fig. 8a). The node analysis results of closed rings showed that there was no statistically significant difference between the results of direct comparison and indirect comparison ($P>0.05$). For node analysis, see the attached supplementary Fig. 3.

NMA

The results of the mesh meta-analysis showed that 276 pair-to-pair comparisons were produced, and the ADR mesh analysis results are listed in the attached Table 1.

Efficacy ranking

SUCRA probability ranking showed ENDOANGEL (97.86%) > AQCS (93.9%) > SD-CADe (83.3%) > CADe + EAC (80.3%) > WingCap

Table 5 Univariate and multivariate regressions examine the influence of factors that influence the potential prevalence of the disease

Covariate	Univariable					Multivariable				
	Coefficients	Lower bound	Upper bound	Std. error	*P* value	Coefficients	Lower bound	Upper bound	Std. error	*P* value
Male	0.99	0.99	1.00	0.0001	0.384	0.99	0.96	1.02	0.002	0.279
size	0.99	0.99	1.00	0.0008	0.478	1.00	0.98	1.01	0.001	0.320
FIT	0.99	0.98	1.00	0.004	0.578	1.008	0.92	1.09	0.006	0.419
History	1.00	0.98	1.54	0.002	0.59	1.01	0.90	1.13	0.009	0.344

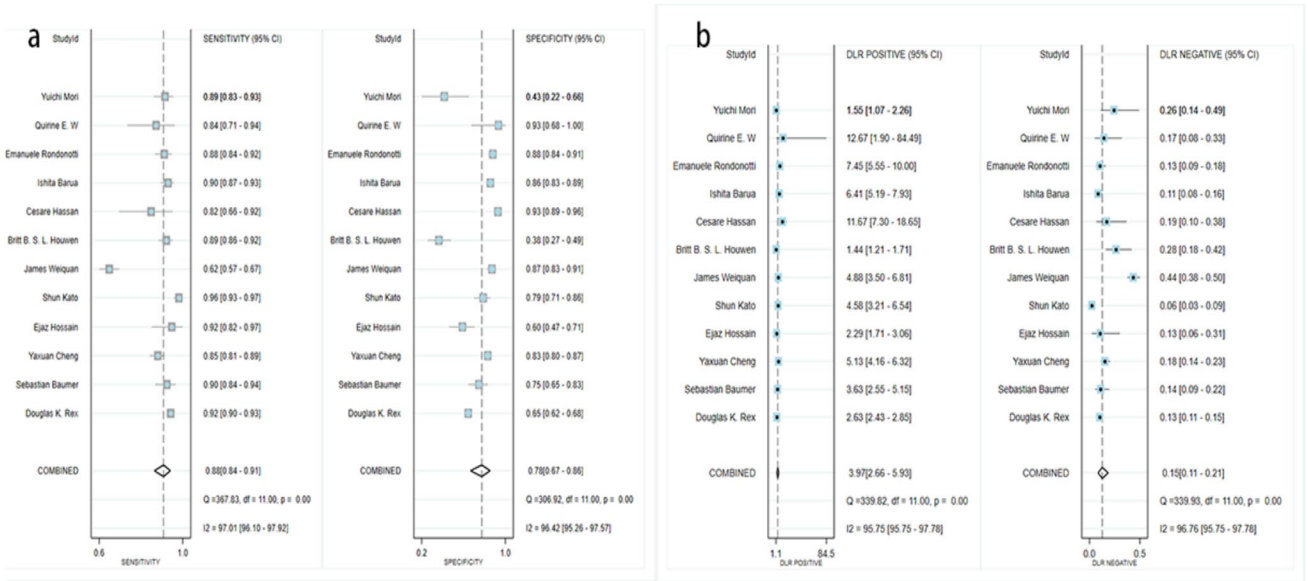

Fig. 5 **a** Combined sensitivity of CADx in the diagnosis of colorectal adenoma; **b** specificity

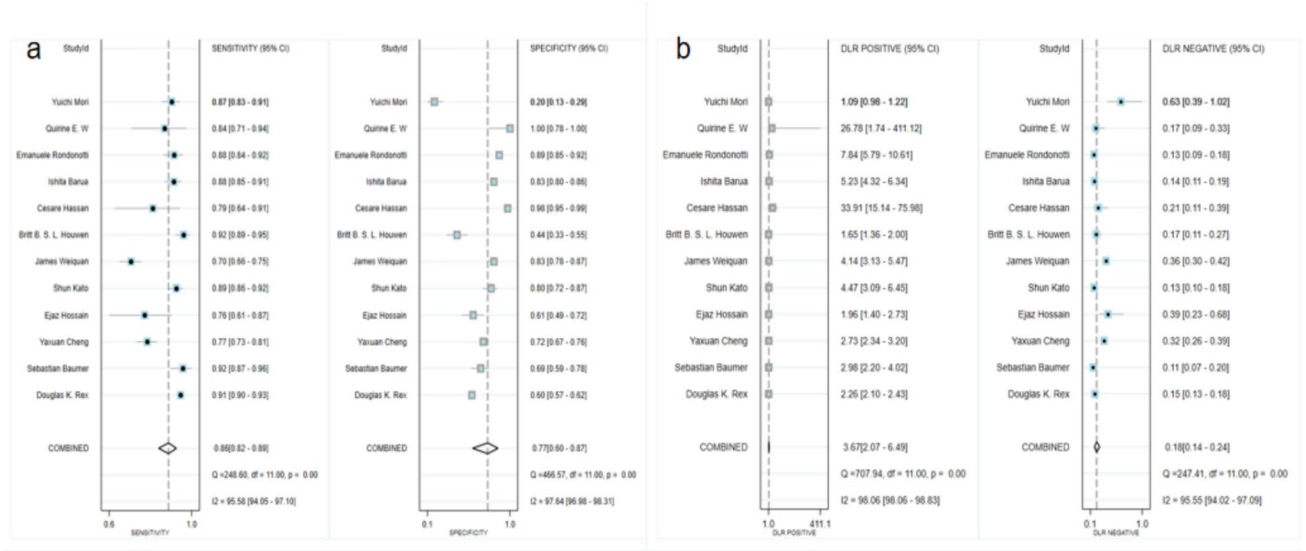

Fig. 6 **a** Combined sensitivity in the diagnosis of colorectal adenomas by physicians; **b** specificity

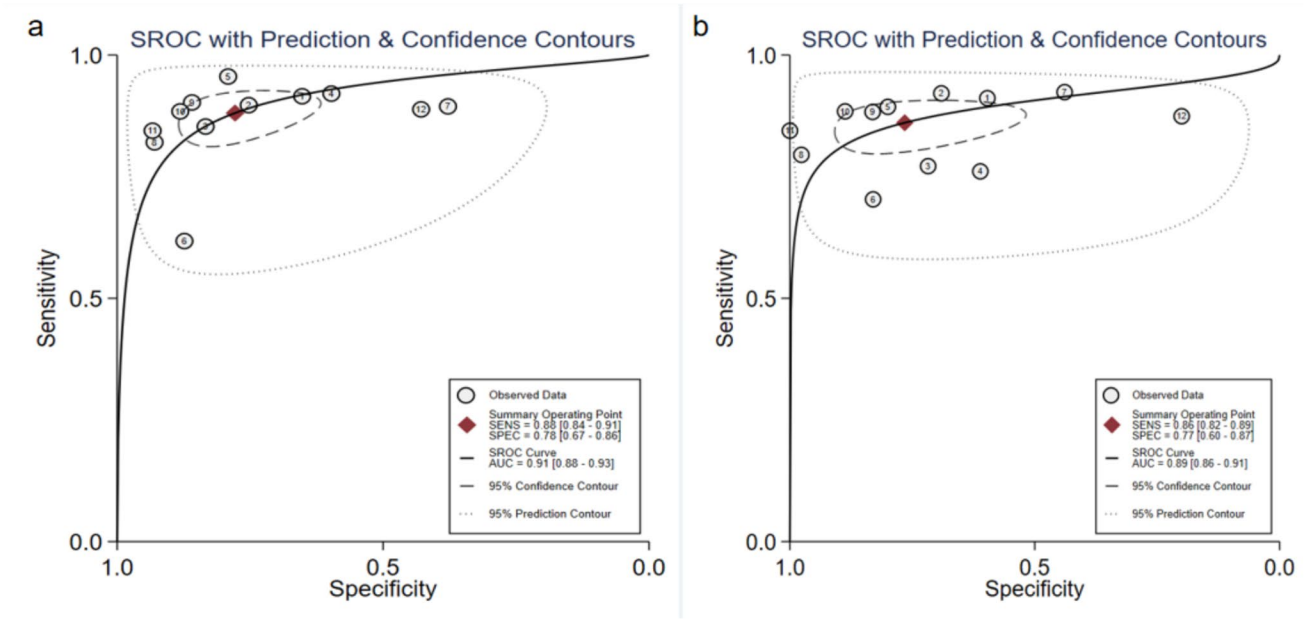

Fig. 7 Subject working characteristic curves of the diagnostic value of CADx-assisted and -unassisted tests for colorectal adenomas

(76.4%) > CM-CADe (69.0%) > ENDO-AID[OIP-1] (66) 0.8%) > EndoScreener (63.5%) > Endocuff-AI (62.9%) > TXI (59.6%) > YOLO V3 (57.3%) > Eagle-Eye (56.9%) > AI (54.4%) > Pancolonic chromoendoscopy (53.2%) > CAD EYE (Fujifilm) (52.5%) > Endocuff (39.5%) > GI Genius (28.2%) > LCI (26.8%) > NBI (23.4%) > EW10-EC02 (14.7%) > HDWL (12.6%) > conventional colonoscopy (11.9%) > WLI (3.2%). The higher the probability, the better the detection effect of colorectal adenoma. The SUCRA figure is shown in Fig. 8b. The SUCRA plot is shown in (Fig. 11a).

PDR

Network evidence graph

Thirty-three studies of RCTs reported PDR, including 20 interventions, with the network relationship overall centered on routine colonoscopy without any adjuncts, with dots representing the intervention, a line connecting the two dots representing the presence of a direct comparison, and the thickness of the line representing the number of

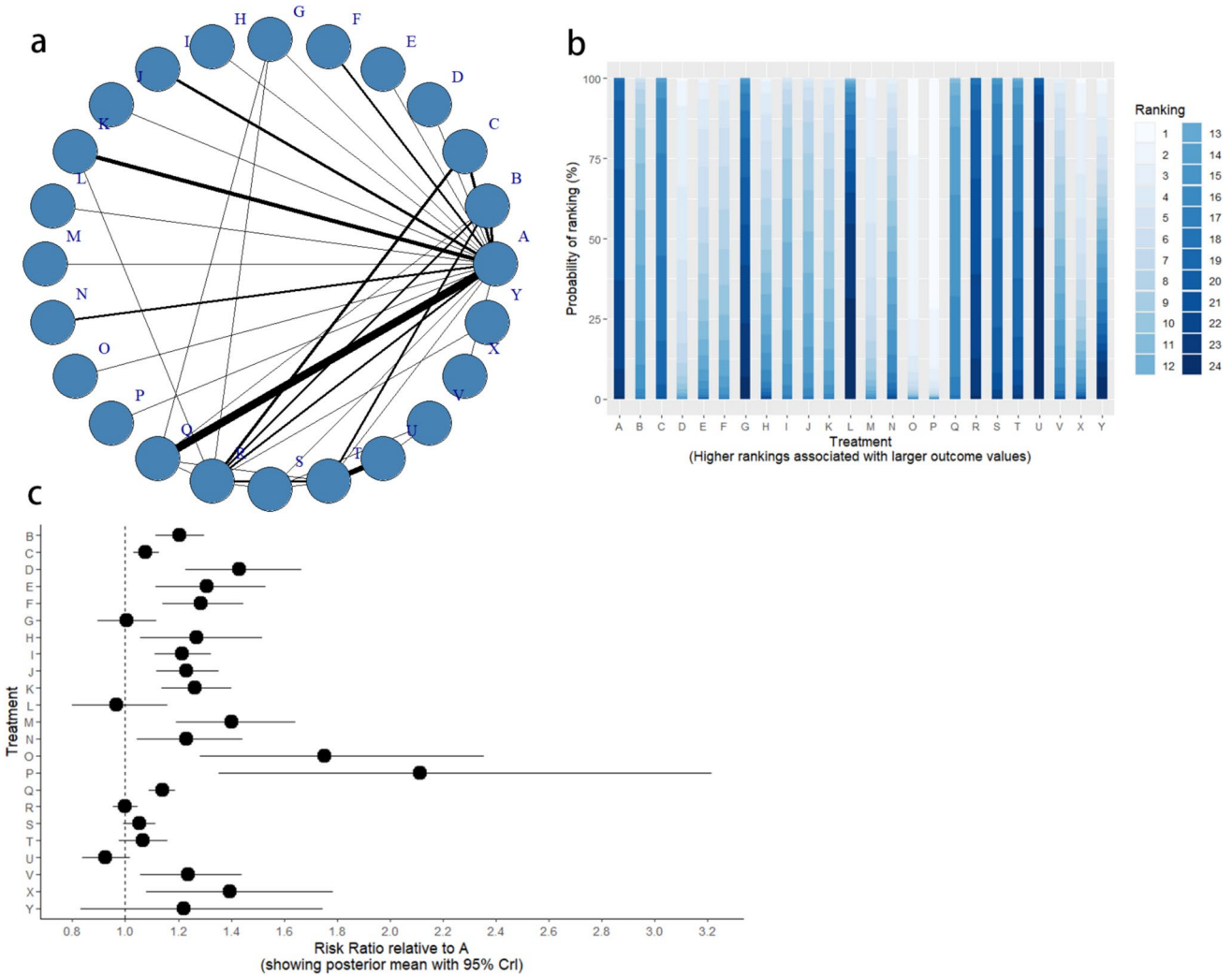

Fig. 8 **a** Network evidence chart. **b** Cumulative ranking SUCRA chart. **c** Forest plot of placebo A compared with different interventions

included studies, which can be seen to contain closed loops, and the network relationship of the evidence is shown in Fig. 9a. The results of the nodal analysis of the closed loops showed no statistically significant difference in results of the direct comparison compared with the results of indirect comparisons; the difference was not statistically significant ($P > 0.05$), and the nodal analysis is shown in Supplementary Fig. 4 in the Appendix.

NMA

The results of mesh meta-analysis showed that 190 pair-to-pair comparisons were generated. The results of PDR mesh analysis are listed in the attached Table 2.

Efficacy ranking

SUCRA probability ranking showed that ENDOANGEL (84.6%) > TXI (82.5%) > EndoScreene (79.7%) > AQCS (78.1%) > NBI (75.1%) > Endocuff-AI (67.5%) > Pancolonic chromoendoscopy (65.6%) > YOLO V3 (59.1%) > WingCap (58.7%) > LCI (56.5%) > AI (55.8%) > Endocuff (32.0%) > EW10-EC02 (27.2%) > WLI (24.6%) > HDWL (23.7%) > HDWL (22.8%) > CNN (21.4%) > CAD EYE (Fujifilm) (11.2%) > conventional colonoscopy (5%), the higher the probability indicates the better effect on colorectal polyp detection. SUCRA graph is shown in (Fig. 9b).The SUCRA plot is shown in (Fig. 11b).

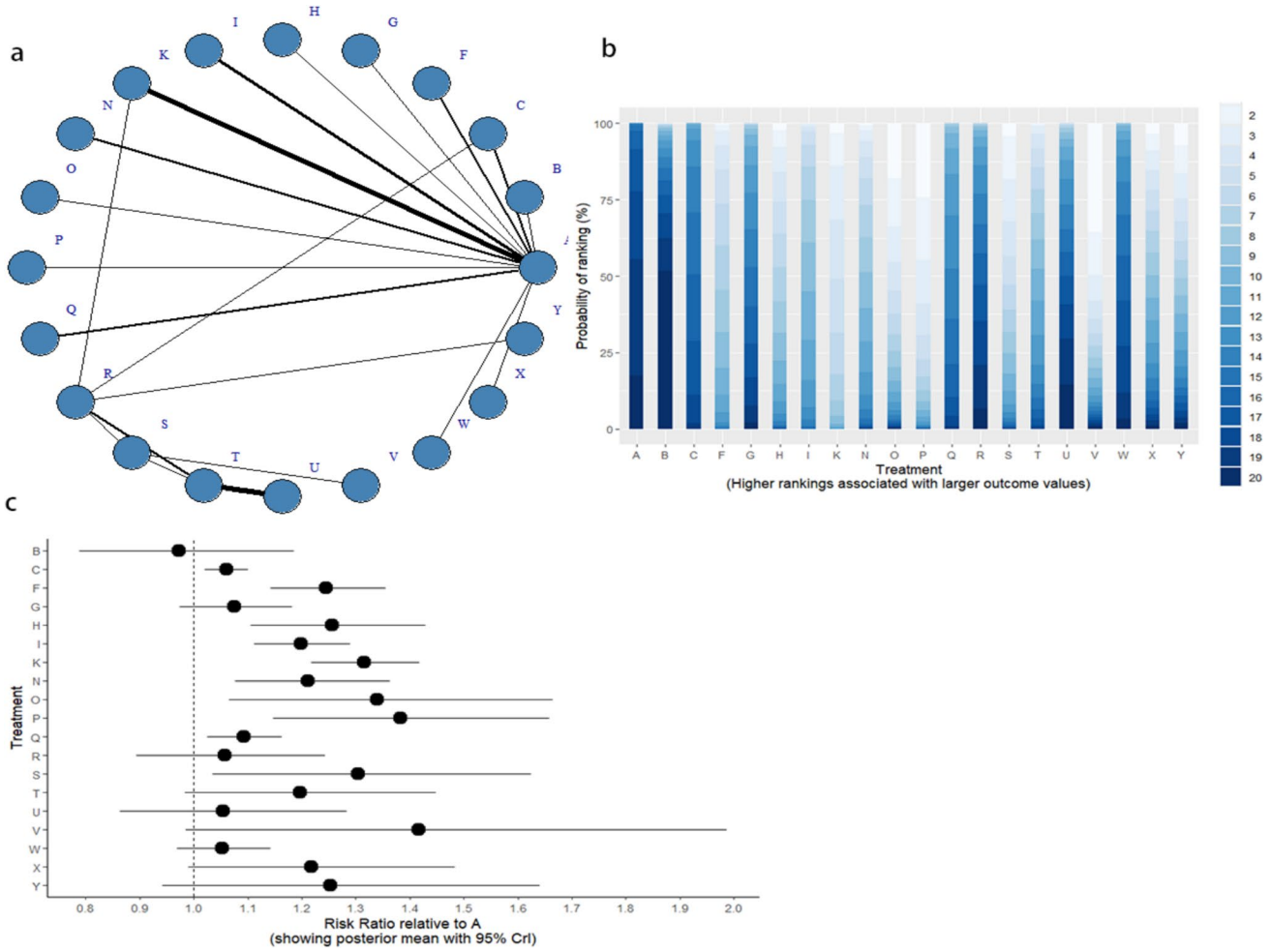

Fig. 9 **a** Network evidence chart. **b** Cumulative ranking SUCRA chart. **c** Forest plot of placebo A compared with different interventions

SSL

Network evidence graph

Twenty-two studies of RCTs reported SSL, including 18 interventions, and the network relationship was overall centered on routine colonoscopy without any adjuncts, with dots representing the intervention, a line connecting the two dots representing the presence of a direct comparison, and the thickness of the line representing the number of included studies, which can be seen to contain closed loops. The network relationship of the evidence is shown in Fig. 10a. The results of the nodal analysis of the closed loops showed no statistically significant difference in the results of the direct comparison compared with the results of indirect comparisons; the difference was not statistically significant ($P > 0.05$), and the nodal analysis is shown in Supplementary Fig. 5 in the Appendix.

NMA

The results of the mesh meta-analysis showed that 153 pair-to-pair comparisons were generated. The SSL mesh analysis results are shown in the attached Table 3.

Efficacy ranking

The SUCRA probability sort shows Endocuff-AI (94.4%) > AI (86.4%) > GI Genius (84.2%) > CAD EYE (Fujifilm) (77.9%) > CM-CADe (69.2%) > NBI (62.2%) > ENDOAID [OIP-1] (58.1%) > EndoVigilant (52.0%) > conventional colonoscopy (49.6%) > HDWL (47.7%) > Endocuff (46.1%) > YOLO V3 (44.7%) > CNN (30.1%) > WingCap (28.5%) > EndoScreener (27.6%) > LCI (25.4%) > TXI (10.4%) > WLI (4.7%); the greater the probability, the better the detection effect of colorectal polyps.

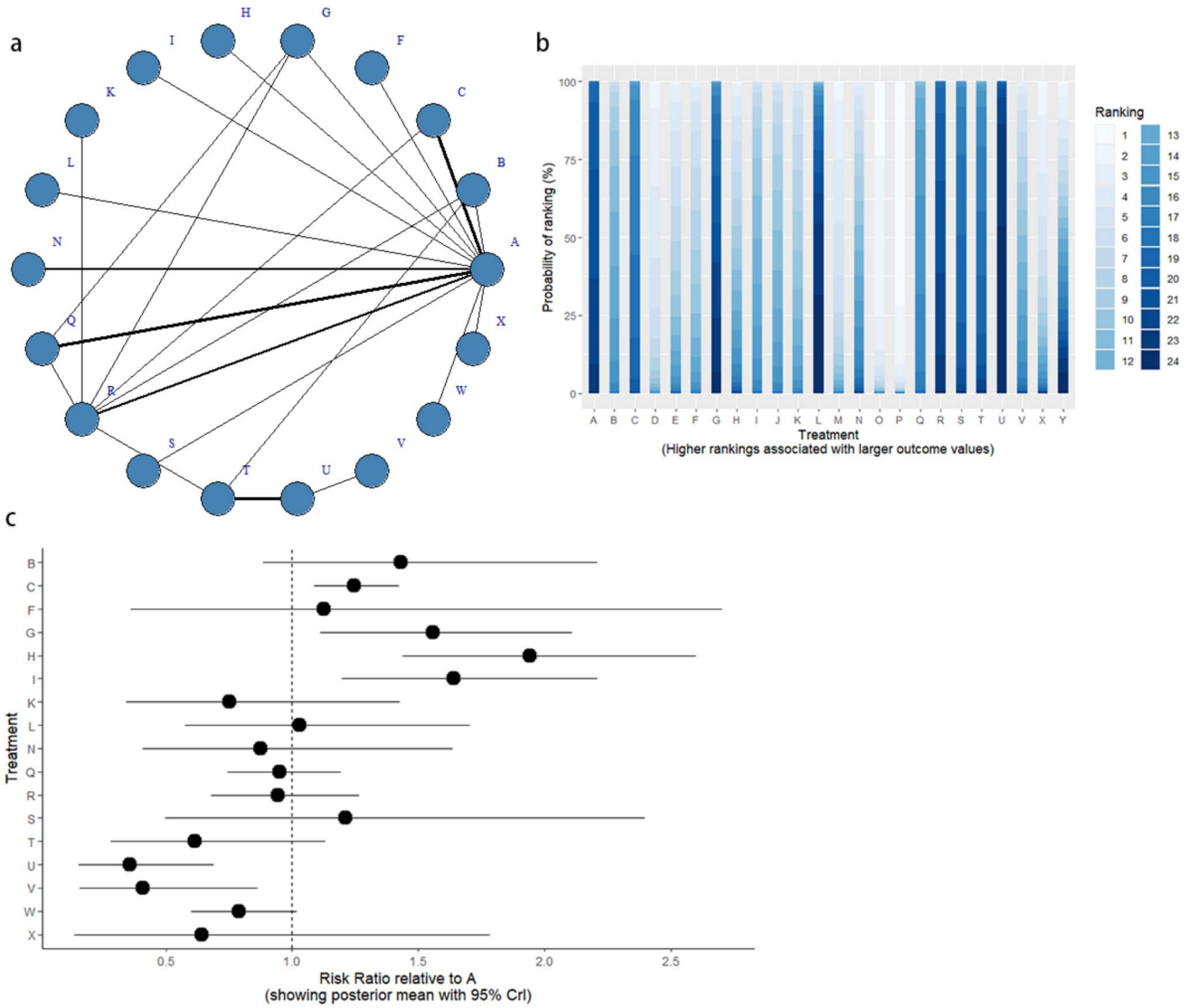

Fig. 10 **a** Network evidence chart. **b** Cumulative ranking SUCRA chart. **c** Forest plot of placebo A compared with different interventions

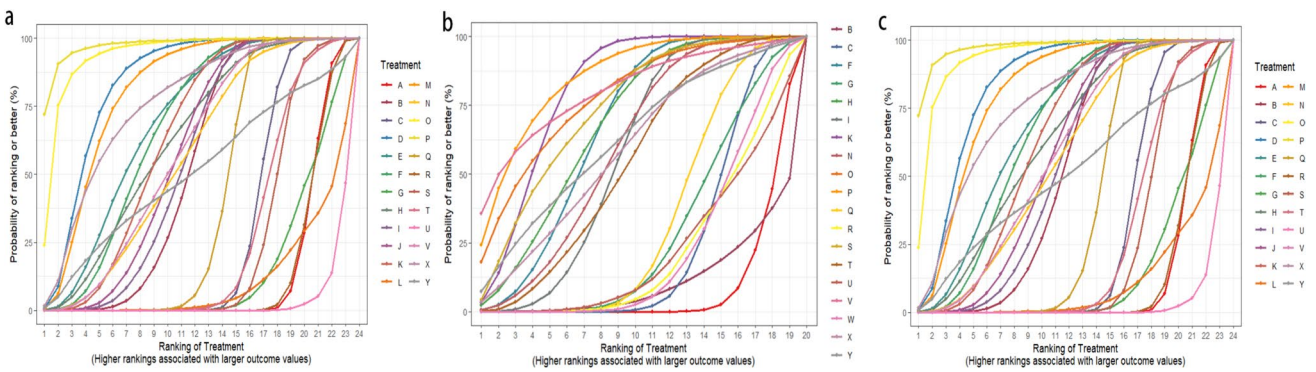

Fig. 11 Heat map of network meta-analysis of each outcome index

The SUCRA diagram is shown in Fig. 10b. The SUCRA plot is shown in Fig. 11c.

Heat map of network meta-analysis

See Fig. 11.

Conclusion

Colonoscopy is the primary screening method for colorectal cancer (CRC), facilitating the detection and removal of both precancerous and cancerous lesions. However, studies on tandem colonoscopy have reported a wide variation in adenoma miss rates (AMR), ranging from 6 to 41% [6]. This variation may be attributed to several factors, including inadequate bowel preparation and the endoscopist's skill, knowledge, and experience—elements that can contribute to the development of CRC even after a colonoscopy. The adenoma detection rate (ADR), defined as the percentage of examinations in which one or more adenomatous lesions are identified, is now widely regarded as the most reliable performance indicator for both endoscopists and individual procedures. Given that ADR is closely linked to the risk of CRC following colonoscopy, various new techniques have been developed to enhance the detection of colorectal lesions. These include high-definition endoscopy [80], mucosal fold spreading devices [81], image-enhanced endoscopy [82], and cap attachment with flaps [83], which help to flatten the colonic folds. In addition, computer-aided diagnostic systems based on deep learning—one of the key methods in artificial intelligence—have garnered significant global research interest in endoscopy, as they can be easily and cost-effectively integrated into conventional endoscopic systems [84]. Computer-aided diagnosis can be categorized into two types: CADe, which assists in lesion detection, and CADx, which supports the differential diagnosis of lesions. CADe facilitates real-time detection of colorectal polyps during endoscopic procedures. A network meta-analysis revealed that [12] CADe increases the adenoma detection rate (ADR) by 7.4% compared to standard colonoscopy, by 4.4% compared to pigmented endoscopy, and by 4.1% compared to mucosal exposure techniques. Moreover, CADe is user-friendly and does not necessitate a steep learning curve, providing a significant advantage over optical pigmented endoscopy methods. While numerous randomized controlled trials have demonstrated the superiority of CADe in detecting polyps and adenomas, its validity has recently come under question. Levy et al. [85] compared adenoma and polyp detection rates during a 6-month period before and after the introduction of CADe (GI Genius) at their high-volume center and found that CADe instead reduced the endoscopist's ADR (30.3% vs. 35.2%) and PDR (36.5% vs. 40.9%). The primary advantage of CADx lies in its capacity to eliminate the necessity for pathology evaluations by facilitating real-time optical diagnosis during colonoscopy. By providing realistic magnification of the polyp surface, CADx can differentiate between neoplastic and non-neoplastic polyps in approximately 40 s. It transmits automated diagnostic signals to the colonoscopist through both acoustic and visual alerts, enabling the identification of neoplastic polyps for removal while permitting small, non-neoplastic polyps to remain in situ [79]. Recent studies have revealed conflicting results [76], indicating that real-time polyp assessment using CADx did not significantly enhance the diagnostic sensitivity for tumor polyps during colonoscopy when compared to optical assessment without CADx (88.4% vs. 90.4%). Consequently, the true diagnostic performance of CADx remains uncertain. This underscores the significance of our study, which aims to evaluate the effectiveness and practical value of CADe and CADx in assisting colonoscopy for detection and diagnosis through a comprehensive meta-analysis.

Our analysis of 52 randomized controlled trials (RCTs) involving 46,177 patients demonstrated that CADe-assisted detection and advanced optical imaging technologies significantly improved adenoma and polyp detection rates compared to conventional colonoscopy. The large sample size enabled us to evaluate the potential benefits of CADe in identifying clinically relevant but infrequent lesions, such as serrated sessile lesions. Based on our findings, CADe appears to be the most promising technique for adenoma detection, surpassing other strategies aimed at enhancing tumor detection contrast or ensuring full mucosal coverage. Furthermore, a comparison of various CADe models revealed that the ENDOANGEL-assisted colonoscopy model achieved the highest detection rate for colorectal adenomas and polyps, with a success rate of 97.8%. The ENDOANGEL system serves as a real-time quality improvement tool designed to monitor the speed and duration of colonoscope withdrawal while alerting the endoscopist to potential blind spots caused by endoscope slippage, thereby enhancing the thoroughness of the procedure. Its key advantages include real-time lesion detection, automatic tracking of withdrawal speed and time during the procedure (rather than merely providing an overall withdrawal duration), and improved detection of small adenomas that might be overlooked during visual inspection, thus reducing human error. In clinical practice, assistants or nurses typically record the times of insertion and withdrawal using stopwatches; however, this information is rarely communicated directly to the endoscopist. The ENDOANGEL system offers real-time feedback, which aids in standardizing the inspection process and reducing variability in endoscopist performance caused by subjective factors or external pressures. This enhancement contributes to improved consistency,

accuracy, and uniformity in lesion detection during colonoscopy [46, 86]. Globally, withdrawal time is a critical metric in colonoscopy guidelines, as it directly affects the quality of the endoscopist's examination of the colorectal mucosa. Both the ESGE and the ASGE recommend a minimum withdrawal time of 6 min to ensure a thorough examination [87]. A multicenter tandem trial in Zhao [88] examined the ADR of 6-min and 9-min decanalization and showed a significantly lower rate of missed adenomas (14.5% vs. 36.6%) and a significantly higher ADR (42.3% vs. 33.5%) at 9 min compared to 6 min. However, more than 80% of colonoscopies have a retraction time of less than 6 min, according to a multicenter clinical study by Xiang et al. [89]. The key to ENDOANGEL-assisted detection lies in its capacity to enhance ADR and PDR by optimizing withdrawal time. Furthermore, the ENDOANGEL system has been extensively utilized in the diagnosis of gastric cancer. In a real-time human–computer competition involving medical video, Wu demonstrated that ENDOANGEL surpassed endoscopists in diagnosing early gastric cancers (EGCs) and performed comparably to them in predicting the depth of EGC infiltration and the differentiation status of these lesions [90]. Additionally, the ENDOANGEL system has shown superior performance in bowel preparation. Zhou et al. [91] used the system to perform bowel preparation scoring every 30 s and calculated the cumulative score ratio upon scope withdrawal. The results indicated that ENDOANGEL achieved an accuracy of 93.33% in assessing the cleanliness of colonoscopy images, significantly surpassing the subjective scoring provided by endoscopists. Enhanced bowel preparation, as evaluated by ENDOANGEL, led to more reliable colonoscopy outcomes with minimal influence from inadequate preparation. SSL are critical precancerous lesions in CRC. However, due to their flat morphology, mucus-covered surface, indistinct borders, and coloration similar to that of the surrounding intestinal mucosa, SSL are often overlooked during diagnosis. Both SSL and traditional serrated lesions are recognized as precursors to the majority of colorectal carcinomas [92, 93]. Among the available modalities, colonoscopy utilizing the Endocuff-AI model has demonstrated the highest detection rate for SSL, at 94.4%. The Endocuff, which received approval from the U.S. Food and Drug Administration in 2012, is a flexible assistive device affixed to the distal end of the endoscope. Measuring approximately 2 cm in length, it features two rows of finger-like flexible "wings" designed to flatten the folds of the bowel wall during scope retraction. This mechanism aids in stabilizing the scope and preventing backward slippage [94]. In the meta-analysis by Chin et al. [95], nine trials involving 5624 patients were reviewed. The study found that, compared to conventional endoscopy, the technique improved the detection rate of serrated adenomas (11.6% vs. 5.6%). However, it was also associated with a higher complication rate (5.47% vs. 0.61%). The complications observed were primarily superficial mucosal injuries, which typically did not lead to more severe outcomes, such as perforation. This study did not specify the AI model employed. Given that the detection rate of SSL was not reported for the ENDOANGEL model, we concluded that the Endocuff-AI model exhibited the highest SSL detection rate in this study. We anticipate that future high-quality studies assessing SSL detection with the ENDOANGEL model will either confirm or challenge our conclusion. Although CADe has enhanced detection rates for ADR and PDR, the most significant improvement has been noted in the detection of small adenomas [96]; however, there has been no substantial enhancement in the detection of advanced adenomas. Furthermore, accurately characterizing small adenomas remains a challenge, with reported accuracy rates falling below 80%, even among specially trained endoscopists, and even lower among non-specialists. This situation contributes to higher rates of unnecessary resections, thereby increasing healthcare costs and the risk of post-resection complications [97, 98]. A key future focus for AI systems is enhancing their ability to differentiate between benign proliferative lesions and clinically significant ones, such as adenomatous polyps and sessile serrated lesions. Nevertheless, it remains essential to increase the overall adenoma detection rate, as this is critical for reducing the risk of colorectal cancer.

While computer-aided detection (CADe) typically employs white light endoscopy for image analysis, computer-aided diagnosis (CADx) integrates several advanced imaging techniques, including magnifying narrow-band imaging (M-NBI), magnifying chromoendoscopy, elastic-scattering spectroscopy (ESS), endocytoscopy (EC), confocal laser endomicroscopy (CLE), and autofluorescence endoscopy (AFE), to facilitate the optical diagnosis of polyps. Optical diagnosis predicts the histopathology of a polyp based on its visual appearance and can serve as an alternative to traditional histopathological evaluation when predictive confidence is sufficiently high. In instances of real-time optical diagnosis, small, low-risk polyps may be discarded after resection without undergoing pathological examination, and non-tumorous polyps located in the rectosigmoid region can be left in situ without resection [99]. Theoretically, CADx-based optical diagnosis improves the accuracy of polyp detection and reduces healthcare costs by minimizing the removal of nonessential polyps. However, in practice, few studies in our analysis demonstrated that CADx significantly outperformed endoscopist diagnoses [69, 70, 77]. The rest of the studies concluded that there was no significant difference in accuracy between CADx-assisted diagnosis and endoscopist diagnosis, and some even noted that the diagnostic performance of CADx was not as good as the diagnostic accuracy of endoscopists [72, 75]. Our final conclusion is consistent

with these findings: CADx assistance did not result in a significant enhancement in the sensitivity and specificity of optical diagnosis. Although the increase in specificity and diagnostic confidence was statistically significant, it was clinically modest. The advantages of CADx may be confined to less experienced endoscopists; considering the associated costs, we do not believe that CADx provides substantial benefits. While our findings raise questions about the overall value of CADx assistance, several studies have demonstrated its effectiveness in identifying small polyps (≤ 5 mm) as adenomas, with a negative predictive value exceeding 90% [79, 100]. This exceeds U.S. and European thresholds for optical diagnostic requirements [99]. This supports the implementation of clinical strategies based on optical diagnosis. Most current studies on CADx systems have been developed and evaluated using expert-preprocessed images and videos, resulting in idealized outcomes that may be challenging to replicate in clinical practice. Consequently, more comprehensive real-world studies are necessary. In conclusion, endoscopists must have a thorough understanding of both the benefits and limitations of AI-assisted technologies to use them effectively in enhancing the quality of colonoscopy.

This study represents the most comprehensive meta-analysis to date on AI-assisted colonoscopy for adenoma detection and diagnosis. It evaluates various CADe models based on detection efficacy and CADx models based on diagnostic accuracy. The inclusion of a wide range of studies—most of which were published in the last 2 years in leading academic journals—reflects the latest advances in the field and significantly enhances the quality of this analysis. However, several limitations must be acknowledged: (1) variations in the qualifications of colonoscopy operators, patient demographics, and examination indications may introduce heterogeneity; (2) some studies did not specify the AI model utilized, which affects subsequent grouping, although we believe this did not impact the overall findings; and (3) the absence of polyp size categorization in certain studies may have influenced the analysis of CADx diagnostic efficacy. In conclusion, CADe-assisted colonoscopy has the potential to improve adenoma detection rates, with ENDOANGEL emerging as the most promising AI model. While CADx assistance resulted in a statistically significant, albeit modest, increase in diagnostic sensitivity and specificity, the clinical relevance remains limited and necessitates further validation through real-world clinical studies.

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Declarations

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