REVIEW

Clin Endosc 2025;58:638-645
https://doi.org/10.5946/ce.2025.022
pISSN: 2234-2400 • eISSN: 2234-2443

Open Access

CLINICAL ENDOSCOPY

Clinical significance of computer-aided quality assessment systems in colonoscopy: a comprehensive review

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Colonoscopy is the primary tool for colorectal cancer screening. High-quality colonoscopy is crucial for the detection of precancerous adenomas; however, the adenoma detection rate varies depending on the skill and experience of the endoscopist. Computer-aided quality assessment (CAQ) uses artificial intelligence (AI) technology to evaluate the quality of colonoscopy examinations. It plays an important role in reducing variations in examination quality and obtaining high-quality colonoscopic images. In this review, we focus specifically on the speedometer, effective withdrawal time, fold examination quality, bowel preparation quality assessment, and cecal intubation with CAQ systems and discuss the role and effectiveness of these systems. CAQ systems are expected to contribute to increase in adenoma detection rates, improvement in endoscopist skills, and standardization of examination quality. However, challenges such as variability in AI performance across different clinical settings and potential overreliance on automated prompts remain key limitations.

Keywords: Adenoma; Artificial intelligence; Colonic polyps; Colonoscopy; Computer-assisted diagnosis

INTRODUCTION

Colorectal cancer is the third most common cancer worldwide, accounting for approximately 10% of all cancer cases, and it is the second leading cause of cancer-related deaths globally.[1] Colonoscopy is widely considered the primary tool for colorectal cancer screening; however, high-quality colonoscopy is essential for effective precancerous adenoma detection.[2] A 1% increase in the adenoma detection rate (ADR) corresponds to a 3% reduction in colorectal cancer risk, underscoring the vital importance of adenoma detection in colorectal cancer prevention.[3]

The European Society of Gastrointestinal Endoscopy lists seven key performance measures as quality indicators for evaluating the quality of colonoscopy examinations: (1) rate of adequate bowel preparation; (2) cecal intubation rate; (3) ADR; (4) appropriate polypectomy technique; (5) complication rate; (6) patient experience; and (7) appropriate post-polypectomy surveillance recommendations (Fig. 1).[4] Computer-aided detection (CADe), an artificial intelligence (AI)-assisted tool, has been shown to increase the ADR.[5-7] Other AI systems designed to enhance quality indicators, such as computer-aided quality assessment (CAQ), have also been developed. CAQ systems leverage AI technology to evaluate colonoscopy quality. These systems enhance polyp detection rates (PDR) by addressing cognitive and visual exposure errors that can lead to missed polyps. CAQ plays a crucial role in minimizing variability in examination quality, promoting high-quality colonoscopy by

Received: January 17, 2025 **Revised:** February 7, 2025
Accepted: February 10, 2025

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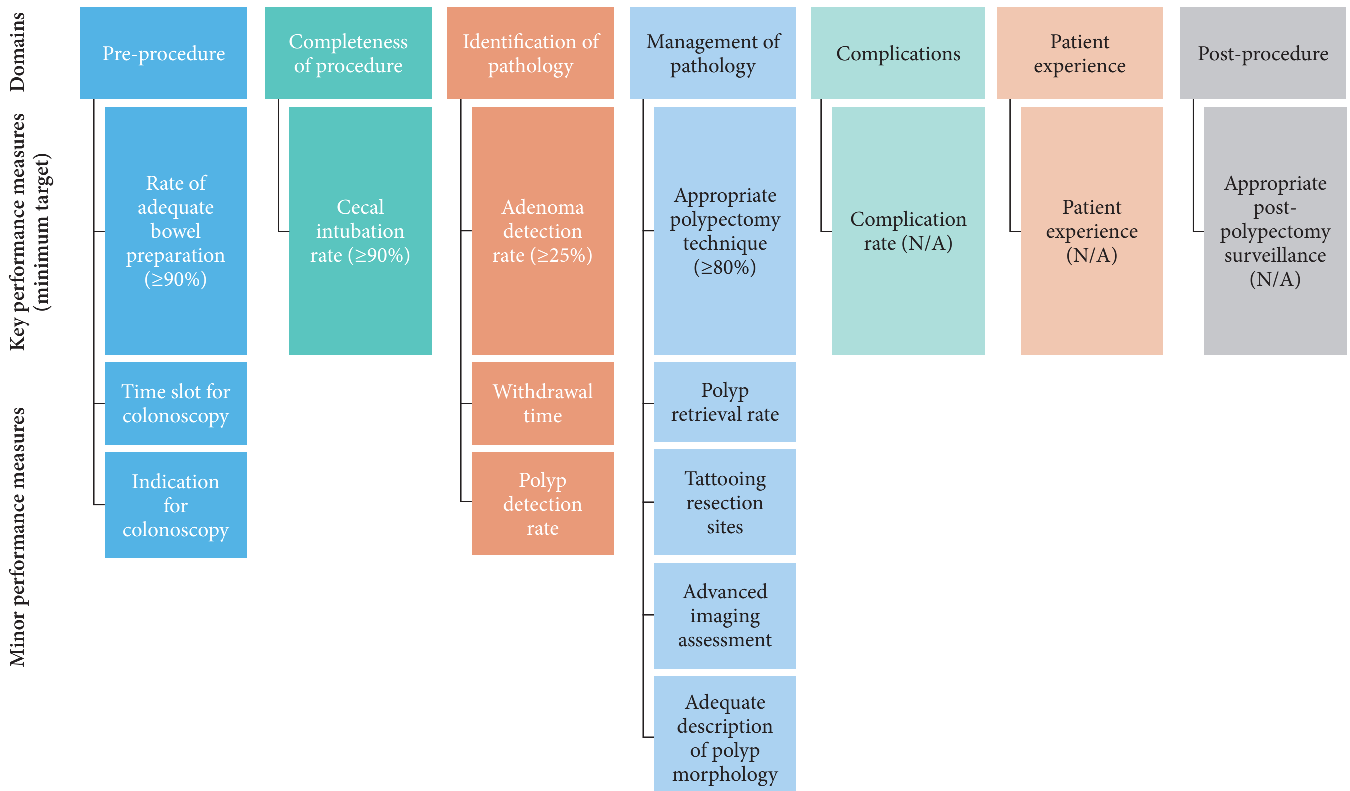

Fig. 1. The domains and performance measures for assessing colonoscopy quality chosen by the working group. N/A, not available. Adapted from Kaminski et al. Endoscopy 2017;49:378–397, with permission.[4]

automatically analyzing endoscopic images and endoscope motion during procedures.[5] This article reviews the key parameters for CAQ assessment in colonoscopy, namely the withdrawal speed (monitored by a speedometer), effective withdrawal time (EWT), fold examination quality (FEQ), bowel preparation scores, and cecal intubation, with an emphasis on the latest evidence (Table 1).[8-22]

WITHDRAWAL SPEED

While a standard minimum withdrawal time of 6 minutes is widely recognized as crucial for optimizing adenoma detection, significant variations in ADR persist among endoscopists, even when the minimum withdrawal time exceeds 6 minutes.[23] Consistently maintaining a stable withdrawal speed throughout the entire procedure is equally important, as fluctuations in speed can increase the likelihood of missed adenomas in specific segments of the colon.[24] Clinically, monitoring the withdrawal speed in real time is challenging for endoscopists, and expert supervision or real-time alerts are not always feasible. Consequently, AI-based speed monitoring systems are being developed to provide real-time alerts when the withdrawal speed exceeds predefined thresholds.

The first software-based automated image analysis tool designed to enhance the quality of screening colonoscopy is colometer, which provides real-time feedback on image clarity, withdrawal speed, and bowel preparation quality by analyzing live video signals from the colonoscope.[8] Filip et al.[8] conducted a study to validate the performance of this tool by comparing colometer's automated assessments with evaluations by expert endoscopists. The findings demonstrated a strong correlation between the system's automated withdrawal speed ratings and those of the endoscopists, indicating colometer's potential for reliable real-time feedback and improved colonoscopy quality, which may ultimately lead to higher ADRs.

Su et al.[9] conducted a randomized trial involving 659 patients assigned to either a control or an intervention group using an automated quality control system (AQCS) based on deep convolutional neural network (DCNN) models. The AQCS included a withdrawal stability monitoring feature that provided re-

Table 1. Types and characteristics of computer-aided quality assessment systems

CAQ parameter	Study	Study design/sample size	Combined with CADe	Outcome measured	Results
Withdrawal speed/bowel preparation quality	Filip et al.[8]	N/A/14 videos	No	Rating of AI for withdrawal speed and bowel preparation quality compared with experts	Strong correlation with endoscopists' ratings
	Su et al.[9]	Randomized controlled trial/659 patients	Yes	ADR	Significant increase in ADR
Withdrawal speed	Yao et al.[10]	Single-center, randomized, four-group, parallel, controlled trial/1,076 patients	Yes	ADR	Significant increase in ADR
	Yao et al.[11]	Randomized, noninferiority tandem trial/685 patients	Yes	AMR	Significant decrease in AMR
	Gong et al.[12]	Single-center, retrospective, observational study/1,804 patients	No	ADR	POF was strongly correlated with ADR
	Barua et al.[13]	Prospective clinical implementation trial/332 patients	No	ADR	No increase in ADR
Effective withdrawal time	Lui et al.[14]	Retrospective study/350 videos	No	ADR	Each 1-minute increase in EWT was associated with a 49% increase in ADR
Fold examination quality	Liu et al.[15]	Prospective observational study/103 videos	N/A	ADR	Significant increase in ADR
Bowel preparation	Zhou et al.[16]	N/A/120 images and 20 videos	No	Experts' BBPS (gold standard) vs. AI-derived BBPS	93.3% accuracy for AI
	Zhou et al.[17]	Prospective, observational study/616 patients	N/A	ADR	Significant inverse correlation between the e-BBPS score and ADR
	Inaba et al.[18]	Prospective validation study/106 patients	No	BBPS	99.0% of the patients achieved a BBPS score ≥ 6
	Zhu et al.[19]	Prospective, single-masked, multicenter randomized clinical trial/524 patients	No	BBPS, ADR	BBPS was higher in the AI group, no significant difference in ADR
	Zhong et al.[20]	Randomized, controlled, endoscopist-blinded method/232 patients	No	BBPS, ADR	BBPS and ADR were higher in the AI group
Cecum recognition	Low et al.[21]	Retrospective study/13,222 images	No	AO detection	94% accuracy in differentiating AO from non-AO images
	Hsu et al.[22]	Cohort study/9,468 participants (without AI), 11,170 participants (with AI)	No	ADR, CIR	Significant increase in ADR, no significant difference in CIR

CAQ, computer-aided quality assessment; CADe, computer-aided detection; N/A, not available; AI, artificial intelligence; ADR, adenoma detection rate; AMR, adenoma miss rate; POF, proportion of overspeeded frames; EWT, effective withdrawal time; BBPS, Boston bowel preparation scale; e-BBPS, electronic BBPS; AO, appendiceal orifice; CIR, cecal intubation rate.

al-time prompts to slow down and re-examine segments when instability or blurry frames were detected. This real-time supervision ensured a consistent and meticulous inspection pace, in the intervention group (28.9%) compared to the control group (16.5%). These findings suggest that the improved withdrawal stability achieved via AQCS directly contributes to an increased

ADR. Furthermore, endoscopists in the AQCS group demonstrated significantly longer mean withdrawal times compared to their baseline withdrawal times before the study.

Real-time speed monitoring effectively synergizes with CADe systems to further enhance the ADR. Yao et al.[10] reported a significantly higher ADR than that in a CADe-only group. This suggests that integrating these technologies offers a reliable approach for maximizing adenoma detection during colonoscopy. Another multicenter tandem trial evaluated the feasibility of AI-assisted colonoscopy performed by novice endoscopists in 685 patients.[11] Each procedure was followed by a repeat colonoscopy performed by AI-assisted expert endoscopists to determine lesion miss rates and ensure patient safety. The adenoma and polyp miss rates were significantly lower in the AI-assisted novice group than in the control novice group (18.8% vs. 43.7%, $p<0.001$ and 21.2% vs. 35.4%, $p<0.001$, respectively). These findings highlight the potential of AI-assisted colonoscopy for improving the withdrawal quality among non-expert endoscopists, leading to reduced reliance on expert supervision, improved detection rates, and enhanced training opportunities.

The proportion of overspeed frames (POF) during colonoscopy withdrawal is a promising quality metric. In one study, a real-time withdrawal speed monitoring system was developed using three DCNN models, with the POF calculated after filtering out frames associated with biopsy and polypectomy procedures.[12] Specifically, the POF was defined as the percentage of frames with an instantaneous withdrawal speed exceeding 44 mm/s. Gong et al.[12] found an inverse correlation between the POF and ADR. When withdrawal time exceeded 6 minutes, the ADR in the group with POF ≤10% was significantly higher than that in the group with POF >10% (25.3% vs. 16.5%; $p<0.01$). These results suggest that the combined assessment of POF and withdrawal time may be a reliable indicator of colonoscopy quality, reflecting both withdrawal stability and mucosal visualization. The POF could become a valuable computer-aided metric for evaluating colonoscopy quality, potentially addressing the limitations of standard withdrawal time alone.

Conversely, a study by Barua et al.[13] involving 332 patients found no significant association between the use of a speedometer and the ADR. This result may have been influenced by the lack of blinding, as observers might have subconsciously altered their behavior by placing additional focus on maintaining a steady withdrawal speed, thereby improving their technique independently of the speedometer's effect on the ADR.

EFFECTIVE WITHDRAWAL TIME

Traditionally, a withdrawal time of more than 6 minutes.[25] However, variations in colonoscope withdrawal speed and technique among endoscopists can significantly affect the reliability of the standard withdrawal time as a predictor of colonoscopy outcomes. This issue is particularly relevant when the withdrawal speed is inconsistent or when maintaining a stable view of the colonic lumen is challenging.[26]

The EWT is a novel quality metric for colonoscopy developed using AI, which offers an objective and reliable measure of colonoscopy quality by accounting for both the withdrawal speed and quality of mucosal visualization. The EWT is calculated by determining the proportion of effective examination frames, defined as frames with a clear view of the colonic wall or lumen, relative to the total number of frames during the withdrawal phase. This metric aims to provide an accurate and objective evaluation of the time spent effectively inspecting the colonic mucosa, thereby enhancing the detection of colonic lesions, including adenomas and polyps.

In a study conducted by Lui et al.,[14] 350 colonoscopy videos were analyzed using a novel AI model (Endoscreener QC; Wision AI), and the findings indicated a significant association between the EWT and ADR. Specifically, the results indicated a 49% ADR increase for each additional minute of EWT. In the future, the EWT may become a promising new quality indicator for colonoscopies.

FOLD EXAMINATION QUALITY

The presence of blind spots is a major risk factor for missed diagnoses during colonoscopy. These blind spots commonly arise from factors such as incomplete mucosal examination, suboptimal bowel preparation, inadequate luminal distension, and excessively rapid withdrawal of the colonoscope.[23] Comprehensive examination of all mucosal folds and flexures through endoscopic rotation is a critical and widely practiced colonoscopy withdrawal technique aimed at minimizing missed diagnoses.[27] Suboptimal inspection of mucosal folds significantly contributes to the non-visualization of polyps due to blind spots during colonoscopy.[28] The effective visualization of areas behind mucosal folds during colonoscope withdrawal is crucial for identifying blind spots. However, real-time supervision of endoscopic examinations of these folds presents considerable practical challenges and is often deemed infeasible.

Liu et al.[15] developed an AI-based system to assess the FEQ by evaluating 103 colonoscopies performed by 11 endoscopists. Three expert endoscopists independently rated the FEQ of each recorded procedure, and these assessments were subsequently compared to the AI system's evaluations. The system's performance was further validated by correlating its FEQ assessments with expert scores, historical ADRs, and withdrawal times. Significant correlations were observed between the AI-generated FEQ scores and expert ratings, as well as historical ADRs and withdrawal time. Notably, AI assistance led to a marked improvement in the FEQ among endoscopists with historically low ADRs (<25%). Therefore, AI-based FEQ offers a promising solution for real-time guidance in the endoscopist withdrawal technique, potentially improving ADRs among endoscopists with previously low ADRs.

BOWEL PREPARATION QUALITY ASSESSMENT

Adequate bowel preparation is a critical quality indicator for colonoscopy and is defined as a Boston bowel preparation scale (BBPS) score of 2 or higher in each of the three colonic segments.[2] Inadequate bowel preparation can significantly compromise colonoscopy quality, increase the risk of missed adenomas, prolong procedure times, and present greater technical challenges. Although the BBPS demonstrates inter- and intra-observer reliability, limitations remain, including subjectivity in endoscopists' assessments, potential recall bias, and lack of consideration for regional variations in bowel preparation within individual colonic segments. Zhou et al.[16] addressed these limitations by developing ENDOANGEL (Wuhan EndoAngel Medical Technology Co., Ltd.), an AI-powered system for bowel preparation assessment. The system was validated using 592 untrained images and tested with 120 images in a human–machine competition against endoscopists. Notably, ENDOANGEL achieved an overall accuracy of 93.3%, outperforming all participating endoscopists. Moreover, ENDOANGEL demonstrated a robust performance in challenging scenarios, achieving 80.0% accuracy on images containing bubbles and 86.0% accuracy in real-time video assessments. The system provides bowel preparation scores every 30 seconds and displays cumulative frame ratios for each score during withdrawal, offering an accurate and objective method for evaluating bowel preparation and potentially enhancing colonoscopy quality.

Subsequently, Zhou et al.[17] investigated the association between the electronic BBPS (e-BBPS) and ADR in 616 patients to establish a threshold e-BBPS score indicative of adequate bowel preparation for colonoscopy screening. The e-BBPS system uses two DCNN models trained to perform two tasks: filtering unstable frames, and classifying acceptable images into BBPS scores of 0–1 (inadequate preparation) and 2–3 (adequate preparation). The final e-BBPS score (0–20) is determined by calculating the proportion of frames classified as having BBPS scores of 0–1, with 5% intervals corresponding to a single e-BBPS unit. The results demonstrated a significant inverse correlation between the e-BBPS scores and ADRs. Patients with e-BBPS scores of ≤3 had significantly higher ADRs than those with scores >3 (28.3% vs. 15.9%, $p<0.001$). These findings suggest that an e-BBPS threshold of 3 may represent an adequate level of bowel preparation, with the ADR exceeding 25%.

The current method for assessing bowel preparation quality before colonoscopy involves visual evaluation of the stool by either patients or medical staff. However, this approach presents several challenges, including subjective variability, patient discomfort with staff inspection of their stool, and an increased workload for medical staff. To address these issues, Inaba et al.[18] developed an AI-powered smartphone application that demonstrated accuracy rates of 90.2%, 65.0%, and 89.3% for grades 1 (solid or muddy stool), 2 (cloudy watery stool), and 3 (clear watery stool), respectively. Moreover, a prospective study involving 106 patients reported that 99.0% (95% confidence interval, 95.3%–99.9%) of the patients achieved a BBPS score of ≥6, indicating effective bowel cleansing.

In another study, Zhu et al.[19] found that an AI-powered application achieved an accuracy of 95.2% and significantly improved bowel preparation quality and patient compliance compared to the control group ($p<0.001$) in a cohort of 524 patients. However, no significant difference was observed in the ADR ($p=0.189$) or PDR ($p=0.223$) between the AI and control groups. In contrast, Zhong et al.[20] demonstrated significantly higher BBPS scores ($p=0.001$) and PDRs ($p=0.020$) in an AI group compared the control group in a sample of 232 patients. These findings suggest that AI-powered smartphone applications have the potential to enhance bowel preparation quality; however, further research is required to clarify their impact on the ADR and PDR.

CECAL INTUBATION

The cecal intubation rate is a critical quality indicator for colonoscopy, with a recommended threshold exceeding 95%.[2] However, with reported rates ranging from 22% to 97%, accurate documentation of cecal intubation is often insufficient, which hinders reliable quality assessment.[29] To address this challenge, Low et al.[21] developed a DCNN capable of identifying the appendiceal orifice as a surrogate marker for cecal intubation and successful colonoscopy completion, even under varying bowel preparation quality. Using a dataset of 13,222 images, the algorithm demonstrated a high sensitivity (0.96), specificity (0.92), positive predictive value (0.92), and negative predictive value (0.96). Notably, the appendiceal orifice detection accuracy rate remained consistently above 95%, irrespective of bowel preparation scores.

In a study by Hsu et al.,[22] the novel AI-based cecal recognition system (AI-CRS) was evaluated for its impact on the cecal intubation rate and ADRs. The study found that AI-CRS was significantly associated with an increased likelihood of detecting both overall adenomas (adjusted odds ratio, 1.35; 95% confidence interval, 1.26–1.45) and advanced adenomas (adjusted odds ratio, 1.23; 95% confidence interval, 1.07–1.41). However, the use of AI-CRS did not show a statistically significant improvement in cecal intubation rates.

LIMITATIONS AND FUTURE DIRECTIONS

CAQ systems have shown promise in improving colonoscopy quality and ADR, but several limitations and methodological concerns must be considered.[30] One major concern is the potential overreliance on AI technology, which may inadvertently reduce endoscopists' independent diagnostic skills.[31] While CAQ provides real-time feedback, excessive dependence on automated prompts may lead to prolonged procedures, disrupting workflow efficiency. In addition, the high costs of AI-enabled systems, including expenses for software updates, cloud-based storage, and personnel training, pose a significant barrier to their widespread adoption, particularly in resource-limited healthcare settings. The seamless integration of CAQ into existing endoscopy units remains a challenge, as variations in colonoscope models and software compatibility can hinder its implementation. Moreover, differences in patient demographics, bowel preparation quality, and endoscopic imaging conditions introduce variability in AI performance across clinical environments, raising concerns about its generalizability.

Another critical issue is the heterogeneity of the study designs used to evaluate the effectiveness of CAQ. The referenced studies included randomized controlled trials (RCTs), retrospective analyses, observational studies, and validation studies based on pre-recorded colonoscopy videos. While RCTs provide high-quality evidence, many studies relied on retrospective datasets, which are inherently limited by selection bias and may not fully reflect real-world clinical dynamics. For instance, studies assessing withdrawal speed metrics often lack real-time applicability, and observer bias may influence the findings of trials involving manual annotation of colonoscopy videos. Sample size disparities further complicate interpretation, with large-scale studies offering statistically robust conclusions, whereas smaller studies with limited data lack sufficient power for definitive findings. Additionally, the absence of standardized CAQ metrics makes direct comparisons between studies difficult because performance measures such as the withdrawal speed, EWT, FEQ, and bowel preparation assessment vary across different research protocols.

To address these limitations, future studies should focus on multicenter validation to assess AI performance across diverse populations and clinical settings. Standardizing CAQ evaluation metrics would enhance comparability and reproducibility, facilitating broader clinical adoption. In addition, developing AI systems capable of real-time adaptability and continuous learning from diverse datasets is crucial for ensuring accuracy in different practice environments. Furthermore, long-term studies investigating the impact of CAQ on colorectal cancer prevention beyond ADR improvements are required to establish its true clinical value. Cost-effectiveness analyses will also play a key role in ensuring sustainable implementations, particularly in healthcare systems with limited resources. By addressing these challenges, CAQ systems can transition from experimental tools to fully integrated components in modern colonoscopy practices, ultimately improving the quality and consistency of colorectal cancer screening.

CONCLUSIONS

CAQ is an essential technology for enhancing colonoscopy quality. It plays a vital role in improving endoscopist skills, standardizing examination quality, enhancing patient safety, ensuring efficiency, and reducing the incidence of colorectal cancer. Additionally, CAQ supports the skill development of less-experienced endoscopists. With further advancements in AI technology, CAQ is expected to evolve significantly in the future, contributing to the early detection and treatment of colorectal cancer. The implementation of CAQ will facilitate the delivery of safer and higher-quality medical care to patients. However, challenges such as cost, integration into existing workflows, and the need for ongoing validation in diverse clinical settings must be addressed before its widespread adoption.

Conflicts of Interest

Katsuro Ichimasa, Shin-Ei Kudo, Taishi Okumura, Yasuharu Maeda, and Masashi Misawa received speaking honoraria from Olympus Corporation. Shin-Ei Kudo and Masashi Misawa have ownership interest in the products of Cybernet Systems. The authors have no potential conflicts of interest.

Funding

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI (grant number: 22K16500).

Acknowledgments

We thank Jane Charbonneau, DVM, from Edanz (https://jp.edanz.com/ac) for editing the draft of this manuscript.

Author Contributions

Conceptualization: WPL, KI, SEK, KGY, MM; Data curation: WPL, KI, YK, TO, YM, YI, MM; Funding acquisition: KI; Methodology: WPL, KI, YK, TO, YM, MM; Supervision: SEK, KGY, MM; Writing–original draft: WPL, KI; Writing–review & editing: all authors.

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