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Retrospective Study

Personalizing withdrawal time by insertion time to achieve target adenoma detection rate in colonoscopy

Withdrawal Time in Colorectal Adenoma

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Abstract

BACKGROUND

Adenoma detection rate (ADR), a key colonoscopy quality metric, varies with patient demographics and procedural factors.

AIM

To identify independent predictors of ≥ 25% ADR, develop a risk model, and propose withdrawal durations based on different insertion times.

METHODS

We retrospectively analyzed 830 cases using logistic regression and identified four key factors, validated in a prospective cohort of 5,699 patients. Their importance was confirmed using Random Forest (RF), EXtreme Gradient Boosting (XGBoost) and Light Gradient Boosting Machine(LightGBM). Attempts to determine target-achieving withdrawal time by grouping cases based on insertion time and Cox regression were inconclusive. Using the 5,699-case dataset, we developed a predictive model combining Support Vector Machine (SVM) with XGBoost. We built a Shiny app using this model for clinical application.

RESULTS

Multivariate logistic regression identified age (OR = 1.05; 95%CI, 1.03–1.08; $P < 0.001$), male (OR = 1.79; 95%CI, 1.32–2.41; $P = 0.005$), higher endoscopist experience (OR = 1.79; 95%CI, 1.20–2.68; $P = 0.005$), and longer withdrawal time ($P < 0.001$) as independent risk factors for colorectal adenoma. A nomogram demonstrated strong discrimination (AUC = 0.720), with robust calibration and decision-curve performance. Feature importance *via* RF, XGBoost, and LightGBM confirmed key predictors. A hybrid model—combining SVM regression for withdrawal-time estimation and XGBoost classification—achieved stable results, with XGBoost reporting AUCs of 0.640 in training and 0.610 in testing, and similar validation outcomes. Deployed *via* a Shiny app for clinical use. However,

model discrimination was modest (AUC 0.61–0.64), suggesting that clinical utility requires further refinement.

CONCLUSION

A hybrid SVM–XGBoost model using four key endoscopic factors was independently validated and is available as a Shiny app, delivering real-time decision support to streamline endoscopy and enhance clinical outcomes.

Key Words: Colonoscopy; Withdrawal time; Insertion time; Adenoma detection rate; Machine learning

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Core Tip: This study identifies four key predictors of ≥ 25% adenoma detection rate (ADR)—age, sex, endoscopist experience, and withdrawal time—and develops a validated hybrid SVM–XGBoost model to predict ADR. Using data from 6,529 colonoscopies, the model demonstrated stable performance and was implemented in a Shiny app for real-time clinical use. This innovative tool offers personalized guidance to optimize colonoscopy quality and improve clinical outcomes, representing a significant advancement in endoscopic decision support.

INTRODUCTION

Colorectal cancer (CRC) is the third most commonly diagnosed malignancy and the second leading cause of cancerrelated deaths worldwide[1], with incidence rising annually and a trend toward younger onset[2]. CRC develops *via* the "adenoma–carcinoma" sequence, typically requiring 10–15 years for an adenoma to progress to carcinoma, thus offering a valuable "golden screening window" for early diagnosis and

intervention[3]. Early prevention, accurate diagnosis, and effective treatment are essential to reduce CRC mortality, with high-quality colonoscopy being pivotal for this purpose. The adenoma detection rate (ADR) is a vital quality metric for colonoscopy and is influenced by multiple factors, including withdrawal time, bowel-preparation quality, the experience level of the endoscopist, cecal intubation rate, patient characteristics, and intrinsic adenoma features[4]. In asymptomatic, average-risk individuals, the recommended ADR target is ≥ 25% (≥ 30% in men and ≥ 20% in women); each 1% increase in ADR is associated with a 3% reduction in CRC incidence[5]. Therefore, a thorough investigation of colorectal adenoma risk factors and the development of an effective risk prediction model are crucial for enhancing colonoscopy quality and enabling early CRC screening.

Cecal intubation time (CIT), also referred to as "insertion time," is defined as the interval from the tip of the colonoscope entering the rectum to its arrival at the cecum[6]. Withdrawal time denotes the duration from the start of scope retraction at the cecum (or terminal ileum) until the tip exits the anus, excluding any additional maneuvers such as chromoendoscopy or polyp biopsy (*i.e.*, "negative" withdrawal time). The 2021 American Gastroenterological Association (AGA) guidelines recommend that, with adequate bowel preparation, the mean negative withdrawal time should be no less than 6 min, although they do not quantitatively account for endoscopist experience or individual patient differences[7]. Preliminary research by our team has identified the key determinants of insertion time as endoscopist factors, patient characteristics, and technical details of scope manipulation—factors that are indirectly reflected in CIT—and has also confirmed a significant impact of insertion time on ADR[8].

This study aims to determine, across different insertion-time intervals, the target-achieving withdrawal time required to achieve an ADR of ≥ 25%, thereby providing a robust theoretical foundation and practical guidance for enhancing colonoscopy quality.

MATERIALS AND METHODS

Study population

This study was conducted in the following two phases at the Digestive Endoscopy Center of Wuxi People's Hospital Affiliated with Nanjing Medical University:

Phase I (Retrospective Observational Study): In Phase I, carried out from January to June 2024, 830 consecutive outpatients undergoing colonoscopy were enrolled. In the retrospective cohort, 1,011 patients met the initial inclusion criteria (listed in section "*Inclusion and exclusion criteria*"). Of these, 3 (0.3%) failed cecal intubation, 36 (3.6%) had a history of colorectal cancer with concurrent colorectal resection, 1 (0.1%) was diagnosed with familial polyposis, 18 (1.8%) had inflammatory bowel disease, and 123 (12.2%) had incomplete endoscopic data. After these exclusions, 830 patients were included in the final analysis.

Phase II (Prospective Study): In Phase II, conducted from September 2024 to April 2025, 5,699 consecutive outpatients undergoing colonoscopy were enrolled. Prospective data collection was completed at submission, while the analysis was still being carried out. In the prospective cohort, 6,712 patients met the initial inclusion criteria (section "*Inclusion and exclusion criteria*"). Of these, 5 (0.1%) failed cecal intubation, 234 (3.5%) had a history of colorectal cancer with concurrent colorectal resection, 3 (0.04%) were diagnosed with familial polyposis, 89 (1.3%) had inflammatory bowel disease, and 682 (10.2%) had incomplete endoscopic data. After excluding these patients, 5,699 were considered in the final analysis.

The study protocol was approved by the Ethics Committee of Wuxi People's Hospital (No. KY24159) and registered with the Chinese Clinical Trial Registry (No. ChiCTR2400091134).

Inclusion and exclusion criteria

The inclusion criteria were as follows: Age 45–75 years and adequate bowel preparation, defined as a total Boston Bowel Preparation Scale (BBPS) score ≥ 6.

The exclusion criteria were as follows: Diagnosis of CRC or a history of colorectal resection; familial polyposis syndromes; inflammatory bowel disease; inadequate bowel preparation (any bowel segment with BBPS < 2 or total BBPS < 6); inability to tolerate the procedure or failure to intubate the cecum; and incomplete clinical or procedural records precluding analysis.

Data collection

In Phase I of the study, we extracted comprehensive patient data comprising basic demographics (age, sex, and body mass index (BMI)), detailed medical history (hypertension, diabetes, hyperlipidemia, nonalcoholic fatty liver disease, coronary artery disease, renal insufficiency, cerebral infarction, hyper- and hypothyroidism, thyroid nodules, chronic obstructive pulmonary disease, rheumatologic and immunologic disorders, psychiatric conditions, benign gastrointestinal tumors, other malignancies, and prior abdominal or pelvic surgery), clinical symptoms at presentation (constipation, abdominal pain, diarrhea, changes in bowel habits, hematochezia, melena, and hematemesis), and personal habits (smoking and alcohol consumption). We also recorded endoscopic procedure-related factors, including the experience level of the endoscopist, bowel-preparation quality as measured by the BBPS, anesthesia or sedation details, CIT, and negative withdrawal time. According to the previous studies conducted on Chinese population, BMI was dichotomized into normal weight (< 24 kg/m^2) and overweight (≥ 24 kg/m^2)[9]. A BBPS score of 6–7 was defined as good bowel readiness, while a BBPS score of 8–9 was defined as excellent bowel readiness. Insertion time was categorized as less than, greater than, or equal to 10 min, and withdrawal time as less than, greater than, or equal to 6 min.

In the prospective phase, we focused on the variables identified as independently associated with adenoma detection in Phase I—namely sex, age, experience level of the endoscopist, and withdrawal time—alongside insertion time.

Bowel preparation

Prior to colonoscopy, all patients underwent pre-procedure evaluation, which included a coagulation profile, infectious disease screening, and electrocardiography. They were placed on a low-residue diet one day before the examination and fasted from food and fluids on the day of the procedure. Bowel preparation consisted of dissolving four sachets of polyethylene glycol–electrolyte powder in 3 L of warm water, which was consumed entirely within two hours 4–6 h before the examination, until clear, watery effluent was achieved. Bowel preparation was assessed based primarily on the BBPS applied during withdrawal following colonic cleansing and suctioning; at this stage, scores were assigned to three colonic segments: The right colon (cecum and ascending colon), the transverse colon (hepatic flexure, transverse colon, and splenic flexure), and the left colon (descending colon, sigmoid colon, and the rectum). Scoring was based on the amount of residual material and the degree of mucosal visibility; each segment was scored from 0 to 3, and the total BBPS score was the sum of the three segmental scores, with higher totals indicating superior bowel preparation quality. A score of 0 denotes that large amounts of solid fecal matter adhere and cannot be cleared, rendering the mucosa invisible; a score of 1 indicates that only a portion of the mucosa is visible, with the remainder obscured by residual feces and/or opaque liquid; a score of 2 signifies that most of the mucosa can be clearly observed, except for small amounts of residual feces and/or opaque liquid covering the lumen; and a score of 3 indicates that the entire segment is completely clean, with no residual feces or opaque liquid and full mucosal visibility. All endoscopists systematically evaluated bowel preparation during colonoscopy using the BBPS.

Procedure

All procedures were performed using an Olympus CV-290 processor and a CF-HQ290I colonoscope, with each examination conducted up to the cecum. Patients were placed in the left lateral decubitus position with knees flexed, and the scope was gently maneuvered to the cecum using standard loop-reduction and torque techniques. Once the appendiceal orifice was reached and the first cecal photograph taken, withdrawal

began with systematic inspection of the colonic and rectal mucosa. Insertion time—defined as the interval from scope entry to cecal intubation—was recorded by a research coordinator using a stopwatch. During withdrawal, the timer was paused for any additional interventions (polyp biopsy, polypectomy, or mucosal cleaning) and restarted immediately afterward. Of the 30 endoscopists in the study, 20 were classified as high-experience (with > 5 years of practice, > 1 000 colonoscopies performed, and a documented ADR ≥ 25%); the remaining 10 were identified as low-experience. All were informed in advance about the monitoring of insertion and withdrawal times and received training on standardized photo-documentation: Capturing the first anal-verge image at scope entry, the first appendiceal-orifice image at scope advance completion, and the final anal-verge image upon withdrawal. Biopsy specimens were fixed in 10% formalin (40% formaldehyde) for histopathological examination. For each case, BBPS score, insertion time, withdrawal time, polyp location, and size were recorded, and pathological diagnoses were documented post-procedure.

Outcome measures

ADR was defined as the number of colonoscopies in which at least one adenomatous polyp was detected divided by the total number of colonoscopies, multiplied by 100%. CIT was calculated from the moment the colonoscope tip passed the anal verge to the time it reached the cecum. Withdrawal time was defined as the actual elapsed time from cecal intubation until the colonoscope tip exited the anus; both insertion and withdrawal times were determined from the timestamps of endoscopic photographs. To ensure that the withdrawal time reflected pure mucosal inspection, any extra maneuvers—such as chromoendoscopy, biopsy, polypectomy, or cleaning—were annotated and excluded by stopping the timer during these interventions and resuming it immediately afterward.

Statistical analysis

Data analysis was performed in R (version 4.4.1). Continuous variables were expressed as mean ± SD, and categorical variables as counts (percentages). Between-group comparisons were conducted using Student's *t*-test or the χ^2 test. Univariate logistic regression identified candidate predictors ($P < 0.05$), which were then entered into a stepwise multivariate logistic regression; odds ratios and 95% confidence intervals were reported, with two-sided $P < 0.05$ indicating statistical significance. Forest plots and nomograms were generated to visualize the model, and receiver operating characteristic (ROC) curves, calibration curves, and decision curves were plotted to assess discrimination, calibration, and clinical utility. For prospective validation, the second-phase cohort was divided into seven subsets, each approximating the sample size of the retrospective cohort, and ROC curves were used to evaluate model performance. RF, XGBoost, and LightGBM algorithms were also applied to confirm factors associated with the ADR.

Patient distributions in both cohorts were first summarized. We then assessed the relationship between ADR and withdrawal time by stratifying insertion times into four intervals (< 180 s, 180–360 s, 360–600 s, and > 600 s) and estimating, within each stratum, the minimum withdrawal time required to achieve a stable ADR ≥ 25%. Subgroup analyses based on the experience level of the endoscopist, patient age, and sex were also performed to determine the corresponding minimum withdrawal times. Next, a Cox proportional hazards model was constructed and its discrimination was assessed by using the concordance index (C-index), which proved suboptimal. Consequently, after comparing multiple machine learning algorithms, we selected SVM and XGBoost to develop predictive models of target-achieving colonoscopy withdrawal time across the continuous insertion-time. Model performance and fit were evaluated using residual plots, predicted-versus-observed comparisons, and receiver operating ROC curve analysis.

Shiny App Implementation and Usage

The Shiny application (https: //xbxmodel.shinyapps.io/xbx_prediction/) offers a streamlined, single-page interface for real-time, personalized prediction of colonoscopy withdrawal time: Users need to input the cecal insertion time (seconds), patient age, sex (dropdown), and experience level of the endoscopist ("Low" or "High") *via* numeric fields and selectors, and then click "Predict Withdrawal Time" to display the model-derived minimum withdrawal time required to achieve ≥ 25% ADR. In pre-procedure planning, the anticipated insertion times can be used to establish withdrawal time targets; during live procedures, the countdown timer (not shown) of the app ensures adherence to the calculated withdrawal time. In post-procedure audit and training, the exported predicted *vs* actual withdrawal time records enable quality-assurance teams to assess compliance, identify training needs, and refine endoscopy protocols.

RESULTS

Clinical characteristics of 830 enrolled patients

Of the 830 patients who underwent colonoscopy, 576 were classified as the non-adenoma group and the remaining 254 as the adenoma group based on endoscopic findings. In the non-adenoma group, 262 patients (45.5%) were men, with a mean age of 60.09 ± 8.10 years, and 252 (43.7%) had a BMI of ≥ 24 kg/m². In the adenoma group, 152 patients (59.8%) were men, with a mean age of 63.13 ± 7.29 years, and 111 (43.7%) had a BMI of ≥ 24 kg/m² (Table 1).

Procedure-related information for 830 colonoscopy examinations

In the adenoma group, 211 (83.1%) colonoscopy examinations were performed by high-experience endoscopists. It was also found that 211 (83.1%) of 254 cases in the adenoma group had good intestinal preparation. In addition, 219 (86.2%) patients underwent the procedure under sedation, 22 (8.7%) had insertion times ≥ 10 min, and 108 (42.5%) had withdrawal time ≥ 6 min (Table 2).

Univariate and multivariate analyses of colorectal adenoma

Univariate logistic regression was performed on the cohort of 830 patients. BMI, history of hypertension, diabetes, hyperlipidemia, coronary artery disease, renal insufficiency, cerebral infarction, hyperthyroidism, hypothyroidism, thyroid nodules, chronic obstructive pulmonary disease, psychiatric disorders, other malignancies, prior abdominal or pelvic surgery, constipation, abdominal pain, diarrhea, altered bowel habits, hematochezia, melena, hematemesis, smoking history, alcohol use, bowel-preparation score, sedation status, and insertion time were found to be not significantly associated with colorectal adenoma (all $P > 0.05$). In contrast, sex, age, history of rheumatologic/immunologic disease, history of benign gastrointestinal tumors, experience level of the endoscopist, and withdrawal time showed significant associations (all $P < 0.05$). These variables were entered into a multivariate logistic regression model, which identified male sex, increasing age, a higher experience level of the endoscopist, and longer withdrawal time as independent risk factors for colorectal adenoma (all $P < 0.05$) (Table 3).

Evaluation of the colorectal adenoma riskprediction model

We visualized multivariate logistic regression results in a forest plot (Figure 2A), and a nomogram incorporating sex, age, experience level of the endoscopist, and withdrawal time was generated (Figure 2C). Discriminative performance, assessed by the area under the receiver operating characteristic curve, was high (AUC = 0.72; Figure 2B). Calibration curves closely followed the ideal reference line, indicating a good model fit (Figure 2D). The decision-curve analysis demonstrated a positive net benefit across threshold probabilities of 10–50%, suggesting clinical utility (Figure 2E). We split the prospective cohort into seven subsets ($n \approx 800$ each) to mirror the retrospective sample size, ensuring stability testing across heterogeneous groups. The overall AUC was 0.700, and the subset AUCs ranged from 0.690 to 0.730 (0.690, 0.730, 0.720, 0.710, 0.690, 0.700, and 0.710 for groups 1–7, respectively; Figure 2F), further confirming robust discrimination and predictive ability of the colorectal adenoma risk-prediction model.

Three machine-learning algorithms

We identified the factors influencing the ADR using RF, XGBoost, and LightGBM algorithms. The following were identified as the top ten predictors in the descending order of importance in the RF model: Withdrawal time, age, smoking history, sex, history of abdominal surgery, BBPS score, alcohol consumption, history of benign gastrointestinal tumors, experience level of the endoscopist, and BMI. In contrast, the following were identified as the most influential features by the XGBoost model: Withdrawal time, age, history of benign gastrointestinal tumors, sex, BBPS score, BMI, insertion time, smoking history, hypertension history, and experience level of the endoscopist. For LightGBM, the leading factors were withdrawal time, age, insertion time, BMI, BBPS score, sex, history of benign gastrointestinal tumors, smoking history, experience level of the endoscopist, and diabetes history. As shown in the ROC curves for the training sets (Figure 3A–C), all three models achieved AUCs close to 1, indicating excellent discrimination. On the test sets, LightGBM demonstrated only a slight decrease in AUC, suggesting robust generalizability. In contrast, XGBoost showed a more pronounced decline, while RF exhibited the largest reduction—indicative of overfitting and weaker generalization. These performance patterns were corroborated by SHAP-value plots (Figure 3D–F). Collectively, machine learning analyses reinforced that male sex, advanced age, higher endoscopist experience, and longer withdrawal time are independent risk factors for colorectal adenoma.

Patient distribution and correlation of insertion and withdrawal times with ADR

The distributions of insertion time, withdrawal time, patient sex, and age in the 830- and 5,699-patient cohorts are shown in Supplementary Figures 1A–E and 2A–E, respectively. Although linear models (Supplementary Figures 1F, G and 2F, G) suggest an overall trend, they do not adequately capture the nonlinear patterns of the data. The generalized additive model yielded the best fit, with its smooth curves flexibly accommodating varying trends—particularly in the midrange—and effectively characterizing the complex relationship between withdrawal time and ADR. Akaike

Information Criterion (AIC) comparisons across models confirmed the nonlinear association between withdrawal time and ADR.

Withdrawal time stratified by insertion-time categories

Figure 4A and Supplementary Figures 3 show the target-achieving withdrawal times required to achieve a stabilized cumulative ADR of 25%, stratified by insertion-time intervals and further analyzed across subgroups of age, sex, and endoscopist experience for the 830-patient cohort. Supplementary Figure 4 presents the corresponding stratified analyses and target-achieving withdrawal times for the 5,699-patient cohort.

Development and evaluation of the target-achieving withdrawal-time model

A Cox proportional-hazards model was fitted in R using sex, age, and the endoscopist experience level as covariates (Figure 4B). However, the C-index values (0.5–0.7) in both the 830- and 5,699-patient cohorts (Figure 4C, D) indicated only a modest predictive accuracy. We therefore developed a hybrid approach combining SVM regression with XGBoost classification, splitting the 5,699-patient dataset 7: 3 into training and testing sets. The SVM regression model demonstrated good performance in predicting withdrawal time, as shown by residual analyses and prediction-versus-observed plots in both sets (Figure 5A–D), particularly within the central 300–380-s range, although it tended to underestimate the extreme withdrawal time values. The XGBoost classifier achieved AUCs of 0.64 and 0.61 on the training and testing sets, respectively (Figure 5E), reflecting consistent but modest discrimination and generalizability between adenoma-detection-positive and adenoma-detection-negative cases, and indicating potential for decision support pending optimization; independent validation on the 830-patient cohort confirmed stable yet slightly variable performance (Figure 5F). Finally, an interactive Shiny application (https: //xbxmodel.shinyapps.io/xbx_prediction/) illustrated that, for a 50-year-old female patient with an insertion time of 300 s and a low-experience endoscopist, the minimum withdrawal time required to achieve ADR ≥

25% was 318.93 s (Figure 5G), demonstrating the model's potential for personalized clinical decision support.

DISCUSSION

Recent advancements in endoscopic technology have made colonoscopy increasingly acceptable for the diagnosis and treatment of GI diseases. Early colorectal endoscopic screening can reduce CRC mortality by 67%[10], making colonoscopy a cornerstone of CRC screening. The ADR is a critical quality metric for colonoscopy and is closely associated with the incidence of interval CRC[11]; higher ADRs correlate with a lower CRC risk[12]. Therefore, elucidating the factors that influence ADR and implementing targeted management strategies are essential for enhancing colonoscopy quality and improving patient outcomes.

The study flow is presented in Figure 1. In Phase I of this study, we constructed a multivariate logistic regression model to predict adenoma detection during colonoscopy, and identified patient age, sex, experience level of the endoscopist, and withdrawal time as independent predictors of adenoma detection.

Several domestic and international studies have shown that ADR during colonoscopy is closely associated with patient sex. Men exhibit a significantly higher ADR than women, a trend that also applies to the detection of polyps, serrated lesions, and CRC[13, 14], with some studies indicating that the male ADR is up to twice that of women[7]. Our findings similarly confirm the strong relationship between sex and ADR. This disparity likely reflects both physiological and lifestyle factors[15]: physiologically, estrogen has been demonstrated to mitigate the risk of colorectal carcinogenesis[16], while lifestyle factors—such as higher rates of high-fat diets, tobacco and alcohol use, and lower levels of physical activity among men—increase the adenoma risk[15]. Moreover, compared with women, men in whom adenomas or serrated lesions are detected at screening colonoscopy face nearly a twofold higher risk of death from CRC[14]. Age is another key determinant of ADR. In our cohort, the mean age of patients with adenomas was 63.13 years; a previous work has shown that

adenoma prevalence rises from 1.72% to 3.59% between ages 30 and 50 before increasing sharply after age 50[17]. Consequently, international guidelines recommend CRC screening for average-risk individuals aged 50–75 years[7], whereas domestic recommendations set the screening age from 40 to 74 years[18]. Notably, the incidence and mortality of CRC in those under 50 years are rising rapidly[19]. Although specific epidemiological data on adenoma trends by age are lacking, early-onset adenoma incidence may likewise be increasing, motivating calls to lower the age threshold for screening. Our results provide preliminary support for this proposal, but larger studies are required to confirm these observations. In addition, some variables show different results in regression and machine learning analyses. Although BMI was non-significant in our multivariate regression ($P > 0.05$), its placement among the top ten predictors in the machine-learning model shows that machine learning can be used to reveal nonlinear and interaction effects; for example, interaction of BMI with insertion time or patient sex influences ADR. This discrepancy suggests latent relationships that merit follow-up using techniques such as partial dependence plots or SHAP interaction analyses.

In addition to patient-related determinants, we evaluated the impact of endoscopist expertise and procedural factors on adenoma detection. Our findings demonstrate that senior endoscopists achieve significantly higher ADRs. Rather than relying solely on case volume or years of practice, we devised a comprehensive, center-specific competency scale through multiple expert consultations to score and stratify operators into "senior" and "non-senior" groups, thereby capturing a more holistic measure of endoscopic proficiency. This approach aligns with domestic data showing marked ADR differences by operator seniority—24.33% in the 5–10-year cohort *vs* 11.57% in those with < 5 years of experience[20]. According to Jennifer *et al*. too, stronger endoscopic skills correlate with higher detection rates for adenomas, non-polypoid serrated lesions, and proximal serrated polyps[21]. A meta-analysis of eight studies confirmed that targeted educational interventions can significantly improve ADR[22]. Another review of 12 trials found that feedback and performance review are associated with ADR

gains[23]. Given our single-center design and limited number of participating endoscopists, more multicenter studies are warranted to further elucidate how operator factors influence adenoma detection.

Withdrawal time, a pivotal quality-control parameter in colonoscopy, has garnered widespread attention. A 2006 observational study published in the *New England Journal of Medicine* demonstrated that endoscopists whose mean withdrawal time exceeded 6 min achieved significantly higher ADRs[24], prompting the adoption of a 6-min minimum withdrawal standard in multiple national guidelines and consensus statements. Subsequent research found that extending withdrawal time from 6 to 9 min increased the ADR from 27.1% to 36.6%, particularly in the proximal colon and among less experienced endoscopists[25]. Similarly, Desai *et al*. reported that, after excluding time devoted to polypectomy and mucosal cleansing, each additional minute of withdrawal corresponded to a 6% increase in ADR[26]. Our team further proposed segment-specific optimization of withdrawal time: Shortening withdrawal in the ascending colon, where lesions are less subtle, while reallocating time toward segments such as the sigmoid colon and rectum, where adenomas are more readily detected[27]. However, withdrawal time is not indefinitely beneficial—ADR gains plateau beyond 10 min[28], and under conditions of poor bowel preparation, prolonging withdrawal does not significantly increase the polyp yield[29]. Moreover, longer withdrawal may prolong the total procedure time, potentially necessitate deeper sedation, and may cause patient discomfort; these trade-offs should be carefully weighed by endoscopy teams. As one of the most controllable and modifiable factors in colonoscopy, withdrawal time—even with a universally recommended minimum of 6 min—remains insufficiently tailored to endoscopist experience and individual patient factors. Hence, developing customized withdrawal strategies for specific clinical scenarios is essential to ensure consistently high ADRs.

Building on this foundation, the present study innovatively incorporated insertion time as a key covariate in our predictive model. von Renteln *et al*. demonstrated that longer CITs corresponded with lower detection rates of both advanced adenomas and

non-advanced adenomas, suggesting that insertion difficulty may compromise subsequent mucosal inspection. Prolonged CIT during colonoscopy serves as a validated surrogate for procedural complexity—reflecting anatomic challenges such as colonic redundancy, loop formation, and adhesions that require additional maneuvers and sedation—and is associated with increased difficulty in adenoma detection[30]. In a multicenter cohort, Choi *et al.* similarly identified insertion time as a surrogate for procedural complexity, reflecting the attentional and cognitive load of the endoscopist and thereby indirectly affecting adenoma detection. The cognitive burden of sustained procedural demands and endoscopist fatigue impairs attentional resources during withdrawal, leading to decreased vigilance and ADR in later or more challenging cases[31]. Fritz *et al.* further showed that when withdrawal time is maintained above average levels, the negative impact of prolonged insertion can be offset by extended withdrawal, underscoring the need to model the interaction between insertion and withdrawal durations[32]. Our preliminary literature review[8] indicated that insertion time is largely determined by patient characteristics, endoscopist factors, and technical nuances—effectively serving as a composite marker of these influences. By stratifying withdrawal time according to insertion time, the allocation of inspection effort can be made proportionate to procedural difficulty: Cases flagged by extended insertion time receive longer withdrawal time, thereby compensating for heightened complexity and attenuated attention, and mitigating the risk of missed lesions inherent to uniform withdrawal time protocols.

However, this study has several limitations. First, the determinants of ADR are multifaceted and complex; because colonoscopies were performed by multiple endoscopists and the sample size was relatively small, we did not observe significant associations for other potential predictors, such as BMI, diabetes, and bowel-preparation score, highlighting the need for larger confirmatory studies. Second, the generalizability and feasibility of our model across different institutions and patient populations remain untested and should be evaluated in prospective, multicenter cohorts. Furthermore, as the model is derived from existing data, its performance in

clinical practice may be influenced by subjective factors such as operator adherence, procedural techniques, and real-time teamwork. In addition, operator adherence to app-generated guidance is yet to be evaluated in routine workflows and may vary by institutional culture and individual practice. Besides, our machine learning model was trained on all colonoscopy cases, both adenoma-positive and adenoma-negative, to predict whether an individual procedure would achieve an ADR ≥ 25%. Detailed adenoma attributes (*e.g.*, size, location, and morphology) are only recorded when a lesion is detected and thus are not available for the negative cases, and their inclusion would introduce post-hoc information and limit real-time applicability. Future work should explore a two-stage modeling approach, in which lesion-specific features refine risk stratification after the initial detection. Finally, our model (AUC 0.64) underperforms the AGA ADR calculator (AUC 0.70); however, it does offer unique real-time personalization of withdrawal time. Hybridizing these approaches could enhance the precision of our model. Future research should explore the integration of real-time quality-monitoring systems or AI–assisted technologies to enable dynamic adjustment and precise recommendation of insertion and withdrawal times, and to assess their effects on long-term CRC incidence and patient survival outcomes.

CONCLUSION

This study discusses a clinical application framework in which, during screening colonoscopy, endoscopists use patient age, sex, operator experience, and actual insertion time—together with the predictive model developed here—to estimate the target-achieving withdrawal duration. We propose a minimum withdrawal time framework personalized by insertion time to achieve ≥ 25% ADR. While the modest discrimination (AUC 0.64) of the model requires refinement, its integration into a Shiny app enables real-time clinical testing. This framework provides real-time decision support: Smooth, low-complexity insertion can maintain a conventional withdrawal time (*e.g.*, 6–9 min), whereas high-difficulty procedures characterized by prolonged insertion should receive an appropriately extended withdrawal (*e.g.*, ≥ 10 min) to ensure

a thorough mucosal inspection, which will maximize ADR and reduce the CRC risk. However, the model, with an ROC AUC of 0.640, has modest discrimination and predictive power. This is an exploratory study, which requires further validation and refinement.

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