



Dynamics of colorectal cancer screening in low and middle-income countries: A modeling analysis from Thailand

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ABSTRACT

Background: Low and middle-income countries face constraints for early colorectal cancer (CRC) detection, including restricted access to care and low colonoscopy capacity. Considering these constraints, we studied strategies for increasing access to early CRC detection and reducing CRC progression and mortality rates in Thailand.

Methods: We developed a system dynamics model to simulate CRC death and progression trends. We analyzed the impacts of increased access to screening via fecal immunochemical test and colonoscopy, improving access to CRC diagnosis among symptomatic individuals, and their combination.

Results: Projecting the status quo (2023–2032), deaths per 100K people increase from 87.5 to 115.4, and CRC progressions per 100K people rise from 131.8 to 159.8. In 2032, improved screening access prevents 2.5 CRC deaths and 2.5 progressions per 100K people, with cumulative prevented 7K deaths and 9K progressions, respectively. Improved symptom evaluation access prevents 7.5 CRC deaths per 100K with no effect on progression, totaling 35K saved lives. A combined approach prevents 9.3 deaths and 1.8 progressions per 100K, or 41K and 7K cumulatively. The combined strategy prevents most deaths; however, there is a tradeoff: It prevents fewer CRC progressions than screening access improvement. Increasing the current annual colonoscopy capacity (200K) to sufficient capacity (681K), the combined strategy achieves the best results, preventing 15.0 CRC deaths and 10.3 CRC progressions per 100K people, or 54K and 30K cumulatively.

Conclusion: Until colonoscopy capacity increases, enhanced screening and symptom evaluation are needed simultaneously to curb CRC deaths, albeit not the best strategy for CRC progression prevention.

1. Introduction

Colorectal cancer (CRC) is one of the leading causes of cancer death globally (Arnold et al., 2017; Bray et al., 2018). Its prevalence and mortality rates are increasing in many low and middle-income countries (LMICs) with a late-stage presentation at first diagnosis (Allemani et al., 2018). However, they are declining or stabilizing in high-income countries such as Austria, Germany, and the USA due to early detection and treatment of polyps, an effective way to prevent the development of carcinoma (Araghi et al., 2019; Arnold et al., 2017; Simon, 2016). Nonetheless, LMICs face constraints in early detection, including insufficient access to early detection and low colonoscopy capacity (Khan and

Lengyel, 2023)—a requirement to confirm CRC diagnosis. However, building colonoscopy capacity takes time and vast resources; thus, preventive and care strategies should be analyzed under limited capacities.

With limited colonoscopy capacity, policymakers should consider improving colonoscopy capacity utilization, which can be achieved in various ways. For example, using the fecal immunochemical test (FIT) as primary screening can reduce colonoscopy demand compared to using colonoscopy as a one-step screening, one of the recommended methods in the USA (Joseph et al., 2018). Many LMICs use FIT as a primary screening method—a low-cost, low-resource-intensive screening test for CRC detection (Schliemann et al., 2021). For all FIT-positive screening results, further confirmation with colonoscopy is needed for the

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diagnosis (Schliemann et al., 2021). The National Cancer Institute (NCI) of Thailand launched a national screening program for CRC in 2017 based on the 2016 recommendations by the USA Preventive Services Task Force—in which the asymptomatic population aged 50–75 years is recommended to get a FIT screening every year (Phisalprapa et al., 2019). Meanwhile, symptomatic and high-risk patients should skip FIT screening and get a colonoscopy directly. However, the estimated colonoscopy demand from this recommendation still exceeds the capacity (Tiankanon et al., 2021).

Colonoscopy can be used for three main indications in LMICs: CRC screening for the asymptomatic population after positive stool-based test, evaluating potential CRC symptoms (i.e., bloody stool, unexplained weight loss, unexplained iron deficiency anemia, decrease in stool caliber), and surveillance of known pathology (Zheng and Rutter, 2012). Each indication consumes resources from the capacity but affects CRC care outcomes differently. Improving colonoscopy utilization in one indication can affect others in the future; therefore, policymakers should devise careful allocation strategies, especially for LMICs with low colonoscopy capacities. Thailand is an example of an LMIC that has improved the adoption of screening programs and increased engagement for CRC screening (Tiankanon et al., 2021). Despite its benefits, increased access to screening also increases required colonoscopies for diagnosis and surveillance, reducing the availability of colonoscopy for screening. There is limited research on the benefits and drawbacks of screening and symptom evaluation under low colonoscopy capacity, while optimal strategies to allocate colonoscopy remain underexplored.

To address this gap, we develop and utilize the Colo-Sim (Colorectal cancer Simulation model) using national-level data from Thailand. We aim to analyze the benefits and harms of colonoscopy utilization strategies under different colonoscopy capacities.

2. Materials and methods

We used a system dynamics modeling approach (Darabi and Hosseini, 2020) to build Colo-Sim, a compartmental population-based model, representing disease progression, screening, and diagnosis under constraints. Below we present the data inputs, model development, and analysis process. We followed the STROBE reporting guidelines.

2.1. Data inputs

We used historical data of the population aged 50 years and older from 2004 to 2021, including population data, annual deaths, and their projections, collected from The Official Statistics Registrations Systems of Thailand's Department of Provincial Administration and the United Nations (Official Statistic Registration System, 2004–2021, 2022; United Nations, Department of Economic and Social Affairs, Population Division, 2022). The Health Data Center (HDC) of Thailand's Ministry of Public Health provided the number of CRC patients diagnosed via screening starting with the implementation of the national FIT screening policy from 2017 to 2021 (Health data center of ministry of public health of Thailand, 2022). We also obtained the most recent data available from 2004 to 2018 for the number of CRC patients diagnosed via symptoms from the HDC and NCI of Thailand (Health data center of ministry of public health of Thailand, 2022; National cancer institute Thailand, 2022). As stated in a previous study, we used a colonoscopy capacity of 200K people/year as the current colonoscopy capacity (Tiankanon et al., 2021). Data for CRC care evaluation, such as prevalence and mortality rate, are not recorded in Thailand. Thus, we estimated them from the literature and calibrated to available historical data. S1 and S2 report all data inputs.

Data stratification included only age, not sex (female/male) or other demographic factors. No institutional review board assessment was needed because no human subjects were involved; data were not obtained through participant interaction.

2.2. Model development

The Colo-Sim model consists of three major components that are discussed below.

2.2.1. Disease progression and mortality

We assume all CRC cases are generated under the adenoma-carcinoma sequence, the most common pathway to CRC (see S4) (Nguyen et al., 2020). Annual disease progression rates between polyp and CRC in each stage were extracted from the natural history model based on Surveillance, Epidemiology, and End Results data (Hur et al., 2007). As each country's adenoma incidence rate differs, we estimated it by calibrating the model to historical data.

The mortality rates of symptomatic and asymptomatic CRC are different. In 2017, the Thai NCI started national screening for CRC. Almost all prior diagnosed cases of CRC were symptomatic. Thus, we estimated the mortality rate for symptomatic diagnosed CRC patients from the most extensive survival analysis available before FIT national policy implementation (Kittrongsiri et al., 2020).

Previous modeling studies in high-income countries considered undiagnosed CRC as asymptomatic CRC. The mortality rate of undiagnosed CRC is equal to that of the population without tumors, assuming all CRC patients are detected before they die when they have symptoms (Knudsen et al., 2021). Since LMICs have low access to screening and symptom evaluation, some symptomatic CRC patients may die without a diagnosis. Thus, we assume that the CRC-caused mortality rate of undiagnosed and asymptomatic diagnosed CRC patients is proportioned to the symptomatic diagnosed CRC in each stage, estimated by calibrating to historical data (see S1–S2).

2.2.2. Screening and diagnosis via symptoms

CRC progression can be interrupted when CRC is diagnosed through screening and symptom evaluation. First, the model utilizes a two-step screening process: FIT and colonoscopy. The primary assessment is the annual FIT screening of the population aged 50–75, which depends on accessibility to FIT screening. The model captures all FIT screening and colonoscopy results, including true positive, false positive, true negative, and false negative. Per guidelines, all positive FIT patients must get a follow-up colonoscopy to confirm the diagnosis as true or false positive (Davidson et al., 2021). Yet, this depends on accessibility to diagnostic colonoscopy and colonoscopy capacity per year. Patients who get a polyp diagnosis can receive a polypectomy and be cured. After undergoing FIT screening followed by colonoscopy for diagnosis, patients who test positive and are diagnosed with CRC are considered asymptomatic and receive treatment. However, they can progress to symptomatic CRC depending on the probability of symptomatic recurrence. Patients with false negative colonoscopy do not receive treatments.

Second, the number of annual symptomatic diagnoses depends on the number of undiagnosed CRCs and the symptomatic detection rate. This rate is the inverse of sojourn time, defined as the time from disease onset to diagnosis (Zheng and Rutter, 2012). Research on estimate of sojourn time of CRC in LMICs is limited. The sojourn time can be used to estimate the screening interval (Zheng and Rutter, 2012). We considered the sojourn time to capture the accessibility of symptom evaluation (see S7).

2.2.3. Colonoscopy capacity and its allocation

Colonoscopy has limited capacity each year and is distributed into three parts based on indications: CRC screening, symptom evaluation, and surveillance. As symptom evaluation and surveillance have higher urgencies, they are prioritized over colonoscopy for screening asymptomatic patients. The colonoscopy availability for FIT screening was calculated using historical data. The estimation was performed by subtracting colonoscopies allocated for symptom evaluation and surveillance from the total capacity. We simplified the number of surveillance colonoscopies based on the National Comprehensive Cancer Network®

(Benson et al., 2022; Ness et al., 2022) (see Table S5).

More FIT screening increases FIT-positive cases, resulting in more diagnostic colonoscopy need. However, the actual colonoscopy performed is limited by the availability of colonoscopy for FIT screening. Due to limited studies, we assumed that patients who are FIT positive but cannot get a diagnostic colonoscopy within a year are considered lost to follow-up as their actual health status and the presence or absence of CRC remain unknown—the one-year assumption is subject to our sensitivity analysis (see S8). Some of these patients may return for a diagnostic colonoscopy without the need to repeat FIT. The remaining lost-to-follow-up individuals would receive a diagnosis only after symptom evaluation. These rates of return from lost-to-follow-up are additional subjects of our sensitivity analyses (see S8).

There are complex interrelationships among the three indications of colonoscopy. As they consume the same resources, improving colonoscopy utilization in one indication can reduce the capacity available for others. For example, more colonoscopies for screening can detect and cure more polyps and CRC, which reduces the required colonoscopy for symptom evaluation. However, it increases surveillance colonoscopy because of the expansion in diagnosed polyps and CRC. More colonoscopies for symptom evaluation will detect and cure more symptomatic CRC, necessitating more surveillance colonoscopies.

2.3. Model assessment and testing

We conducted several steps to build confidence in the model. First, we performed twenty interviews with nine experts in gastroenterology, colorectal surgery, health policy, and CRC modeling in Thailand and the USA to review the model structure. We collected each expert's feedback to refine the model and then revised the model for the following interview. We also replicated historical data (see S5), through which unknown parameters were estimated. Additionally, we followed established model evaluation guidelines for system dynamics models (e.g., unit consistency and extreme condition analysis) (Sterman, 2018). We followed best practices for transparency and reproducibility of simulation modeling (Jalali et al., 2021; Jalali et al., 2020) to facilitate the replication of this analysis—see the supplementary document for all data and modeling details. We also created an online model interface to run the model without any software requirement (see the link in the data availability statement).

2.4. Projected outcomes

We projected two primary and two secondary outcomes (Table 1) from 2023 to 2032.

2.5. Baseline analysis

We used the model to project potential future trajectories of CRC care from 2023 to 2032. We assumed that accessibility to diagnosis (i.e., accessibility to FIT, diagnostic colonoscopy, and symptom evaluation) remains constant at their last historical values in 2022. We also considered an alternative baseline assumption as a gradual increase in those variables, multiplying them by a 10% annual growth rate (See S6).

2.6. Strategy analysis

We performed a strategy analysis on allocating colonoscopy capacity for improving screening and symptom evaluation access. We compared the effects of *screening access improvement* (hereafter, strategy-I), *symptom evaluation access improvement* (strategy-II), and *combined* strategies (Table 2). Based on expert inputs, we assumed that each strategy would take three years to reach its full potential. We analyzed each strategy under two colonoscopy capacities: 1) the fixed 200K people/year and 2) a gradual increase of capacity over three years, from current to sufficient capacity, estimated from the maximum colonoscopy demand from each

Table 1

Primary and secondary outcomes in the Colo-Sim model, descriptions, and implications.

	Outcomes	Description	Implication
Primary	Annual CRC deaths (<i>people/year</i>)	Total deaths from CRC and non-CRC cause in both undiagnosed and diagnosed CRC patients per year	Reflecting the number of prevented CRC deaths
	Annual CRC progressions (<i>people/year</i>)	The total number of high-risk polyp patients who turn to new CRC per year	Reflecting the number of prevented CRC progressions
Secondary	Total CRC (<i>people</i>)	Total number of undiagnosed and diagnosed CRC patients each year	Reflecting the total healthcare burden of CRC, which depends on annual CRC deaths and progressions
	Undiagnosed CRC (<i>people</i>)	Number of undiagnosed CRC patients each year	Reflecting hidden healthcare burden of CRC, which depends on total CRC and access to detection

strategy (see S7). We estimated the projected outcomes of each strategy compared with the baseline, i.e., the percent change of cumulative CRC deaths, the percent change of cumulative CRC progressions, the percent change of total CRC, and the percent change of undiagnosed CRC.

2.7. Sensitivity analysis

We conducted a sensitivity analysis on strategies I-II and their combination to assess colonoscopy utilization's potential benefits and harms. These parameters were increased from baseline to target value (defined in Table 2). We estimated primary outcomes on 10-year cumulative changes compared to baseline (i.e., the percent change of cumulative CRC deaths and cumulative CRC progressions). We also calculated secondary outcomes in the next ten years (i.e., the percent change of total CRC and undiagnosed CRC). Finally, we conducted one-way sensitivity analyses on estimated parameters through calibration and assumed values in the model (see S8).

3. Results

3.1. Overview of the model

The Colo-Sim model, shown in Fig. S1, is divided into two main sectors: the population with tumors (including polyps and CRC) and without tumors. The population with tumors splits into six subgroups: undiagnosed, diagnosed by symptoms, diagnosed by screening, FIT true positive, loss to follow-up (after screening), and symptomatic after colonoscopy. People can transition from one state to another at a dynamic rate based on the principle of differential equations (see S4). The model can replicate historical data with an average mean-absolute-percentage-error of 13% and R^2 of 80% (see S5).

3.2. Baseline analysis

Fig. S4 represents projected outcomes in the baseline over 10 years. Annual CRC deaths (per 100K people) increase by 32%, resulting in 301K cumulative CRC deaths. Annual CRC progressions (per 100K people) increase by 21%, resulting in 433K cumulative CRC progressions. Total and undiagnosed CRC (per 100K people) are projected to increase by 30% and 25%, respectively. The number of people with FIT positive per year will increase by 18%, while the availability of colonoscopy after FIT will decrease by 24%. We report the projections of the alternative baseline in S6.

Table 2
Description of analyzed strategies using Colo-Sim model and associated parameters and sources.

Strategies	Description	Parameters in Colo-Sim model	Baseline value*	Target value for strategy	Source for target value
I: Screening access improvement	Improving access to screening from our estimated status quo (or baseline) to a higher target level. The target is based on an achievable level in Thailand (Khuhaprema et al., 2014). Improving access to CRC diagnosis among symptomatic individuals.	Accessibility to FIT	3%	62%	(Khuhaprema et al., 2014)
		Accessibility to diagnostic colonoscopy	10%	72%	(Khuhaprema et al., 2014)
II: Symptom evaluation access improvement	We increased the current status quo (assumed to be one) to a higher level that can result in a mean sojourn time of five years in 2032 (assuming to reach the USA level; reported to be five years during 1997–2010).	Accessibility to symptom evaluation relative to the baseline	1	3.43	(Zheng and Rutter, 2012; Brenner et al., 2011), Estimation [†]
Combined improvement	Combination of both strategies above				

* See estimations in S6.

† see estimations in S7.

3.3. Strategy analysis

Fig. 1. presents the projected effects of strategies compared to baseline over 10 years under the current and sufficient colonoscopy capacities.

3.3.1. Current colonoscopy capacity

Strategy-I (red line in Fig. 1) prevents 2.4% of cumulative CRC deaths (7K people) (a) and 2.0% of cumulative CRC progressions (9K people) (b). In addition, it reduces 0.3% of total CRC (1K people) (c) and 8.2% of undiagnosed CRC (20K people) (d) in 2032.

Strategy-II (green line) prevents CRC deaths cumulatively by 11.6% (35K people) (a). However, it does not prevent any CRC progressions (b). This strategy also increases by 9.1% in total CRC (35K people) (c), with an 18.2% reduction in undiagnosed CRC (46K people) (d) in 2032.

The combined strategy (purple line) reduces 13.6% of cumulative CRC deaths (41K people) (a) and 1.5% of cumulative CRC progressions (7K people) (b). Also, it causes a 9.0% increase in total CRC (34K people) (c) with a 22.4% reduction in undiagnosed CRC (56K people) (d).

Counterpart reports of these results in per 100K are presented in Table S6.

3.3.2. Sufficient colonoscopy capacity

To satisfy demand in each strategy presented in Table 2, we estimated that 681K people/year is a sufficient capacity.

Strategy-I (red line in Fig. 1) prevents 6.6% of CRC deaths (20K people) (e) and 6.9% of CRC progressions (30K people) (f). Moreover, it reduces 2.5% of total CRC (10K people) (g) and 32.5% of undiagnosed CRC (81K people) (h) in 2032.

Increasing colonoscopy capacity does not affect strategy-II outcomes (green lines). During 2022–2028, it reduces undiagnosed CRC more than strategy-I; however, it reduces undiagnosed CRC less than strategy-I after 2028 (h).

The combined strategy (purple line) produces the best results in primary outcomes by reducing 18.0% of cumulative CRC deaths (54K people) (e) and 6.8% of cumulative CRC progressions (30 K people) (f) in 2032. However, it causes a 6.4% increase in total CRC (25K people) (g) with a 42.7% reduction in undiagnosed CRC (107K people) (h) in 2032 (see S7). We report the results of strategy analysis based on the alternative baseline in S7.

3.4. Sensitivity analysis

Fig. 2 and Fig. 3 show sensitivity analysis results for the combination of two strategies: strategy-I (x-axis) and strategy-II (y-axis), where the parameters of each strategy change from the baseline to target values. We present primary outcomes based on 10-year cumulative changes compared to the baseline below (for secondary outcomes, see S8). Simultaneous improvement in strategies produces mixed results

depending on the level of access improvement, outcomes, and colonoscopy capacity. We present the outcomes under the current (200K, left plots) and sufficient (681K, right plots) colonoscopy capacity.

3.4.1. Current colonoscopy capacity

Fig. 2 shows that strategy-I slightly decreases cumulative CRC deaths, i.e., up to 2.4% at any level of strategy-II implementation. Moreover, its effect weakens when strategy-I is closer to its target value (the end right of the x-axis). Strategy-II decreases the cumulative CRC deaths (up to 11.6%) more. Fig. 3 shows that strategy-I decreases cumulative CRC progressions (up to 2%) at any level of strategy-II implementation. Yet, strategy-II does not affect cumulative CRC progressions when strategy-I is close to its baseline value—some minor effect appears when strategy-I gets closer to its target values (up to 0.5%).

Fig. S9 shows that strategy-I slightly decreases total CRC (up to 0.3%), while strategy-II linearly increases total CRC (up to 9.1%) (see S8). Fig. S10 shows that strategy-I decreases undiagnosed CRC (up to 8.2%); however, its effect weakens when strategy-I is closer to its target values. Strategy-II also decreases more undiagnosed CRC (up to 18.2%) (see S8).

3.4.2. Sufficient colonoscopy capacity

Fig. 2 shows that simultaneous increases in strategies I-II decrease cumulative CRC deaths (up to 18%). Fig. 3 shows that strategy-I decreases cumulative CRC progressions (up to 6.9%). However, strategy-II does not affect cumulative CRC progressions at any strategy-II access level.

Fig. S9 shows that strategy-I decreases total CRC (up to 2.5%). However, strategy-II increases total CRC (up to 9.1%). Fig. S10 shows that simultaneous increases in strategies I-II decrease undiagnosed CRC (up to 42.7%) (see S8).

4. Discussion

This study is the first that quantifies the potential effects of CRC early detections under constraints, including insufficient access to CRC detections and low colonoscopy capacity. We showed that, during 2004–2022, there was low access to FIT screening, colonoscopy after FIT positive, and colonoscopy for symptom evaluation in Thailand. In 2022, the fraction of people who received FIT screening was only 3%. Also, 10% of FIT-positive patients received colonoscopies to confirm the diagnosis. These two estimates are often much higher in developed countries, e.g., in the USA, 67% and 50–87%, respectively (Lin et al., 2021). Access to symptom evaluation was also estimated to be 29% of that in the USA.

Over the next decade, projected outcomes (i.e., CRC deaths, CRC progressions, total CRC, and undiagnosed CRC) will increase by more than 20%, attributed to the aging population. Due to the increasing demand for colonoscopy for symptom evaluation and surveillance, the remaining capacity of diagnostic colonoscopy is projected to be reduced

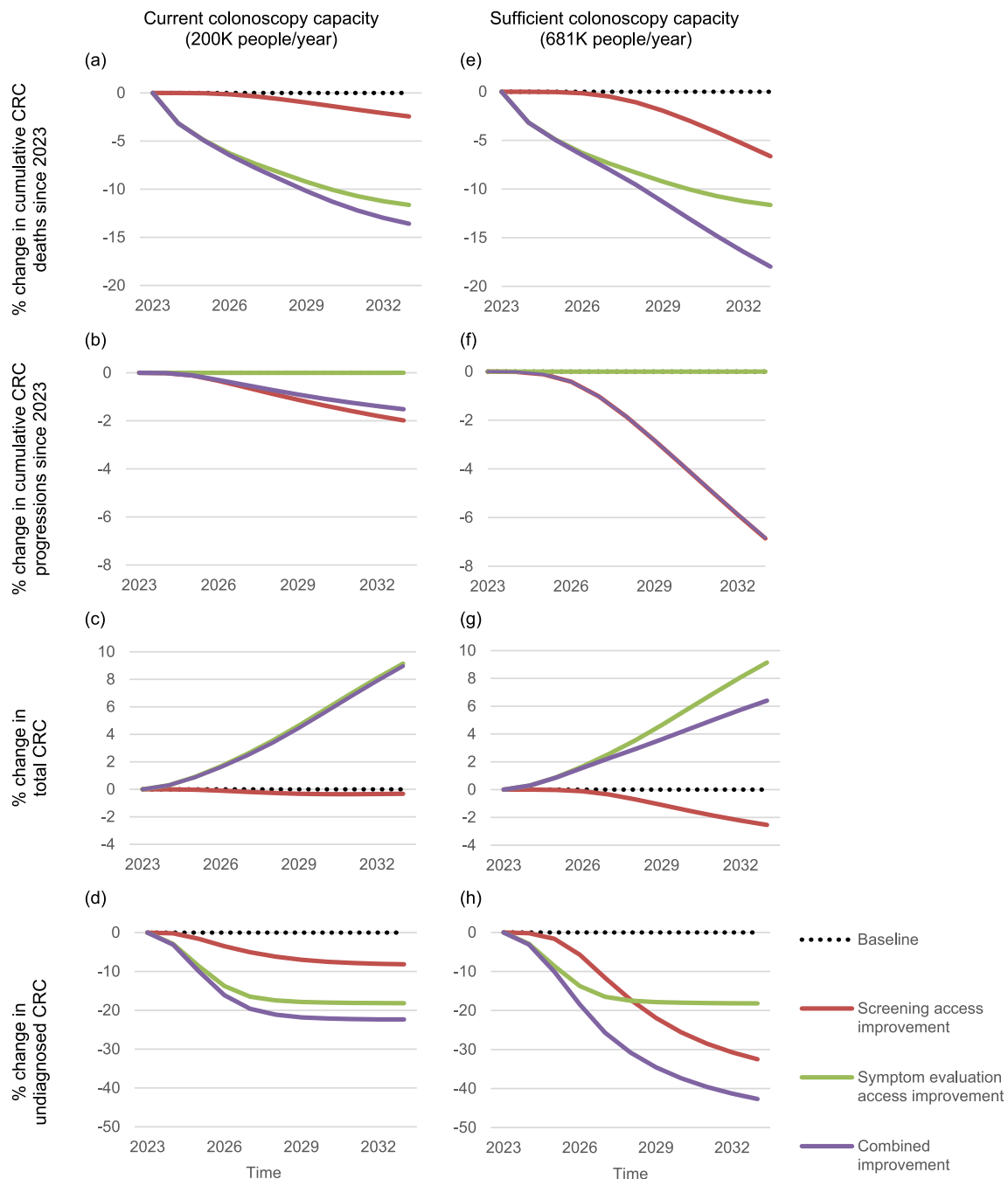


Fig. 1. Simulated outcomes over 10 years for strategies compared to baseline, evaluated under current and sufficient colonoscopy capacities, for the Thai population aged 50 and older. Percent change in cumulative CRC deaths since 2023 (a, e); percent change in cumulative CRC progressions since 2023 (b, f); percent change in total CRC (c, g); and percent change in undiagnosed CRC (d, h)). Trajectories from each strategy are compared to baseline, under current (200K people/year) and sufficient (681K people/year) colonoscopy capacities.

by 24%. In other words, colonoscopy capacity is already low, but demand fulfillment will worsen over the next ten years.

Our results show that, with the current colonoscopy capacity, there are pros and cons among the three strategies: screening access improvement (strategy-I), symptom evaluation access improvement (strategy-II), and their combination.

There are tradeoffs between strategy-I and the combined strategy. For primary outcomes, strategy-I results in low CRC death prevention (2.4%) but the highest CRC progression prevention (2.0%). The combined strategy results in the highest CRC death prevention (13.6%) but lower CRC progression prevention (1.5%). For secondary outcomes, strategy-I

is the only strategy that reduces total CRC (0.3%). The combined strategy results in higher total CRC (9.0%), as it is, 6 times stronger in preventing CRC deaths than CRC progressions. Additionally, strategy-I decreases undiagnosed CRC (8.2%), while the combined strategy decreases undiagnosed CRC (22.4%). Unlike strategy-I, strategy-II worsens primary and secondary outcomes more than the combined strategy.

Increasing colonoscopy capacity from current to sufficient capacity augments the effects of strategy-I and the combined improvement. However, the outcomes of strategy-II are not affected by increases in capacity since the current capacity satisfies its demand. With sufficient colonoscopy capacity, the combined strategy produces the best results in

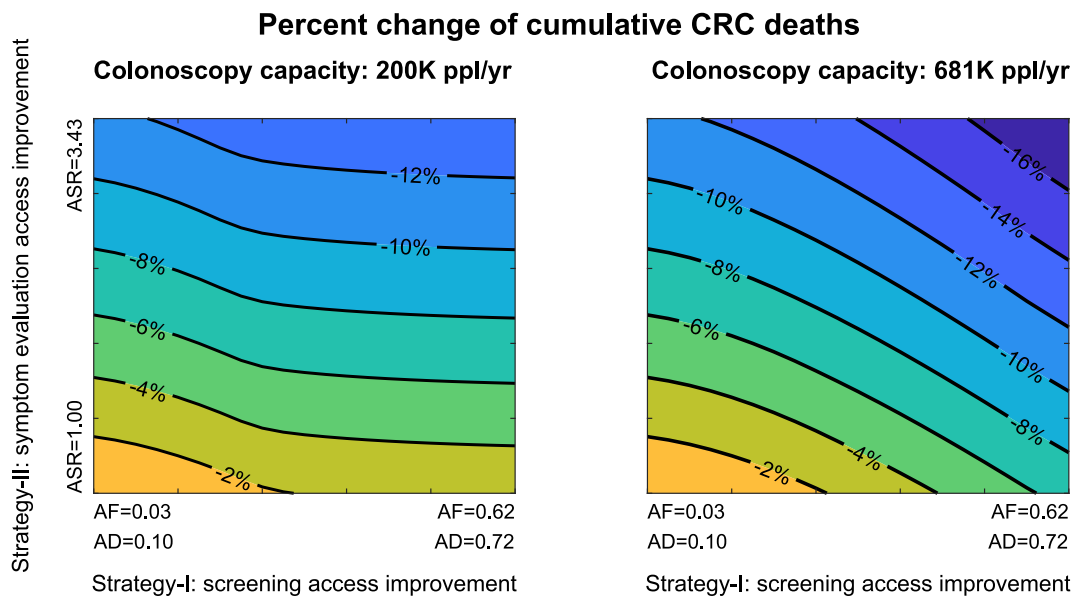


Fig. 2. Results of the sensitivity analysis for the combination of Strategies I and II, illustrating projected changes in cumulative CRC deaths among the Thai population aged 50 and older from 2023 to 2032. Strategy-I: screening access improvement; Strategy-II: symptom evaluation access improvement. The parameters of each strategy change from the baseline to target values. AF: accessibility to FIT; AD: accessibility to diagnostic colonoscopy; ASR: accessibility to symptom evaluation relative to the baseline.

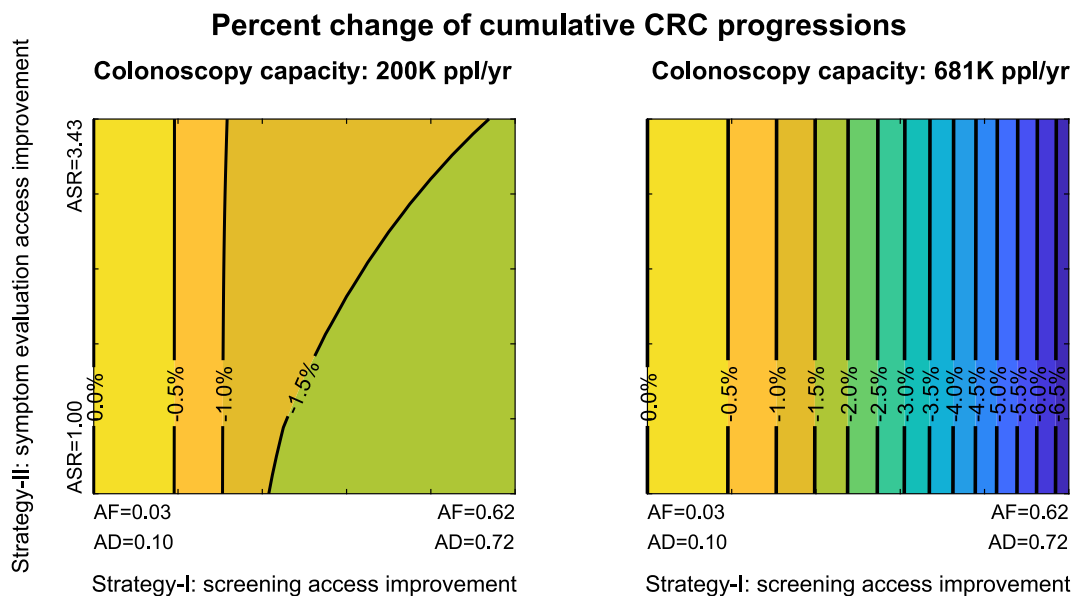


Fig. 3. Results of the sensitivity analysis for the combination of Strategies I and II, illustrating projected changes in cumulative CRC progressions among the Thai population aged 50 and older from 2023 to 2032. Strategy-I: screening access improvement; Strategy-II: symptom evaluation access improvement. The parameters of each strategy change from the baseline to target values. AF: accessibility to FIT; AD: accessibility to diagnostic colonoscopy; ASR: accessibility to symptom evaluation relative to the baseline.

primary outcomes and undiagnosed CRC. However, the projected total CRC will increase (reaching 6.4% in 2032).

In sensitivity analyses, we simultaneously increased strategy-I and II from their baseline level to target value. The results showed that, under the current capacity, the effect of strategy-I on CRC deaths is noticeable only slightly after the baseline value. However, approaching the target value, colonoscopy demand outweighs capacity, correlating with a decreased effect on CRC deaths. On the other hand, strategy-II has a higher impact on CRC death prevention while having minimal effect on CRC progressions. When strategy-I is close to the target value, strategy-II slightly increases CRC progressions as colonoscopy capacity falls short of satisfying demand. Since colonoscopy for symptom evaluation has

higher priority than screening, further improvement in strategy-II increases colonoscopy demand for symptom evaluation, resulting in lower remaining capacity for screening and, as such, less impact from strategy-I. However, these dynamics are changed when colonoscopy capacity is increased to a sufficient level. Both strategies I-II reduce CRC deaths over ten years. Interestingly, for CRC progressions, strategy-II has almost no effect (i.e., it does not increase CRC progressions), while even a small increase in strategy-I results in fewer CRC progressions, in other words, more CRC prevention.

Our study has limitations. We simplified the model by only using the adenoma-carcinoma sequence for the average-risk population; because data for other alternative pathways (i.e., disease progression, prognosis,

and prevalence of CRC generated) for high-risk population (e.g., population with first-degree relative being CRC, Lynch syndrome, inflammatory bowel disease) were not available in Thailand. Other missing data included annual polyp and CRC detection in each stage from screening, annual CRC deaths in each stage, and annual undiagnosed CRC deaths (Health data center of ministry of public health of Thailand, 2022; National cancer institute Thailand, 2022). Moreover, we had only five data points of CRC screening (annually during 2017–2021), not enough to scrutinize the complex relationship between CRC screening and other contexts, such as the COVID-19 pandemic. Furthermore, our model focuses on the national level, and we did not stratify the analysis by sex, socioeconomic status, and other factors. Additionally, the details of colonoscopy capacity improvement, such as the number of doctors who can perform colonoscopy, and access to colonoscopy provided by various medical specialists (e.g., gastroenterologists vs. surgeons) in different healthcare facilities in Thailand, were not considered.

Ethics statement

This study did not involve human participants or animals. All data used in this study was obtained from publicly available sources or previously published literature, and no new data was collected for this study.

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CRediT authorship contribution statement

Peeradon Wongseree: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Zeynep Hasgul:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – review & editing. **Borwornsom Leerapan:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Cherdsak Iramaneerat:** Conceptualization, Validation, Writing – review & editing. **Pochamana Phisalprapa:** Conceptualization, Validation, Writing – review & editing. **Mohammad S. Jalali:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Colo-Sim and data used in this analysis are available at <https://github.com/zhasgul/colosim>. An online interface to run the model without any software requirement is also available at <https://mj-lab.mgh.harvard.edu/colo-sim-model>. Additional analysis details are reported in the online supplementary document.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jpmed.2023.107694>.

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