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RESEARCH

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Optimizing strategy for cervical cancer prevention in china: a comprehensive modeling analysis

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Abstract

Background With the first domestic 9-valent human papillomavirus (HPV) vaccine soon to be introduced in China, alongside advancements in cervical cancer screening technologies, we aimed to evaluate and identify effective, cost-effective, and affordable cervical cancer prevention strategies suitable for China.

Methods We developed a Markov model from the healthcare system perspective, comprising 18 ages strata and 9 health states, to predict the effectiveness, cost-effectiveness, and affordability of 38 different cervical cancer prevention strategies over the next 30 years, compared with no intervention. The model parameters were calibrated using least-squares fitting against real-world data and simulation results for the no-intervention scenario. Strategies were assessed and selected based on the World Health Organization's (WHO) cervical cancer elimination target (incidence < 4 per 100,000), cost-effectiveness threshold (Incremental cost effectiveness ratio [ICER] < one-time China's 2023 per capita GDP), and current cervical cancer prevention budget in China. We conducted one-way and probabilistic sensitivity analyses, and considered potential price reductions from centralized procurement to assess the robustness of the results.

Results Compared with no intervention, 16 strategies could achieve cervical cancer elimination by 2050, 29 were highly cost-effective, and 11 were affordable. Overall, only screening women aged 35–64 using visual inspection with acetic acid (VIA) combined with bivalent vaccination for girls aged 9–14 met all criteria. This strategy could achieve cervical cancer elimination by 2041, with an ICER of US$2,543.91 per quality-adjusted life-year (QALY), and was deemed affordable. Sensitivity analysis indicated the results were robust. If price reductions from centralized procurement were considered, CareHPV, PAP, and 9-valent HPV vaccination could become attractive alternatives.

Conclusion Screening women aged 35–64 with VIA and vaccinating girls aged 9–14 with the bivalent HPV vaccine is currently the most suitable cervical cancer prevention strategy for China. In scenarios with larger budgets, more accurate screening methods and the 9-valent HPV vaccine could be introduced. Our study provides crucial evidence for cervical cancer prevention and control policy in China.

Keywords Cervical cancer, Markov model, Screening, Vaccination

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Introduction

Cervical cancer is the fourth most common cancer among women globally, with over 660,000 new cases in 2021, and approximately 20% of these cases occur in China [1]. HPV vaccination and early cervical cancer screening have been shown to significantly reduce the incidence of cervical cancer [2]. In many high-income countries, the effective implementation of these strategies has led to reductions in cervical cancer incidence by as much as 80% [3]. In 2020, the World Health Organization (WHO) launched the Global Strategy to Accelerate the Elimination of Cervical Cancer, proposing that by 2030, 90% of girls aged 9–14 should be vaccinated against HPV, 70% of women should undergo cervical cancer screening, and 90% of those diagnosed with precancerous lesions or cancer should receive appropriate treatment and care (the 90–70–90 targets) [4]. The ultimate goal is to reduce cervical cancer incidence to fewer than 4 per 100,000 women per year, thereby achieving elimination. Many developing countries, including China, have formulated cervical cancer prevention strategies based on WHO recommendations and their local circumstances, with some initial progress made [5, 6].

China began implementing cervical and breast cancer screening programs for rural women in 2009. However, after over a decade, these programs have only covered 10–20% of eligible women (aged 35–64 years), far below the WHO-recommended target of 70% [7]. In recent years, some economically developed regions in China, such as Shenzhen, have introduced free HPV vaccination for girls aged 9–14, but a national immunization program has yet to be established [8, 9]. Because these initiatives have been limited in scope and still in exploratory phases, the incidence and mortality rates of cervical cancer in China have not been effectively controlled over the past decade [1]. Recognizing this, the Chinese government has incorporated cervical cancer screening into the national basic public health services, ensuring sustainable funding for prevention efforts [10].

With the release in 2024 of China's first domestically produced 9-valent HPV vaccine (covering HPV types 6, 11, 16, 18, 31, 33, 45, 52, and 58), alongside advancements in cervical cancer screening technologies and the anticipated demographic changes in China, identifying effective, cost-effective, and affordable prevention strategies is a top priority for cervical cancer control in the country [11]. Common cervical cancer screening techniques, such as visual inspection with acetic acid (VIA) and Pap smears, have been widely used in the "Two-Cancer Screening" program. Although inexpensive, these methods have lower accuracy. Liquid-based cytology (LBC) and HPV DNA testing (e.g., Hybrid Capture 2 [HC-2]), which have higher accuracy, are recommended by both Chinese and U.S. guidelines but remain costly and are primarily used in wealthier regions of China [12, 13]. Newer technologies, such as CareHPV and p16 testing—recommended by U.S. guidelines—have shown promising accuracy but are similarly expensive [14, 15]. The availability of China's first domestically produced bivalent HPV vaccine (covering HPV types 16 and 18), introduced in late 2019, and the forthcoming 9-valent HPV vaccine, which have similar efficacy to imported vaccines, will alleviate the high costs and limited supply of imported vaccines, offering new hope for cervical cancer prevention. However, further evidence is needed to guide their implementation [11].

Most studies on cervical cancer prevention in mainland China have relied on virtual strata simulations, which do not fully account for future changes in population demographics and the impact of HPV vaccination [8, 10, 16–18]. While these studies have provided valuable insights into the effectiveness and cost-effectiveness of different strategies, they have not considered the affordability of implementing these strategies. Importantly, all prior studies were completed before the availability of China's first domestic 9-valent HPV vaccine, thus not taking this significant development into account.

Our study aims to address these gaps by constructing a Markov model with 18 ages strata and 9 health states to predict the effectiveness, cost-effectiveness, and affordability of 38 different cervical cancer prevention strategies over the next 30 years, compared with no intervention. We aim to identify strategies that meet the criteria of effectiveness, cost-effectiveness, and affordability, and provide recommendations for cervical cancer prevention strategies in China.

Methods

Overview of study

We conducted a model-based analysis from the healthcare system perspective, as shown in Fig. 1.

Intervention strategies

We defined no intervention as the current situation in China, where HPV vaccination coverage is approximately 3% and screening coverage is very low (10–20%) [7, 19].

As illustrated in Fig. 1, our study included 38 intervention strategies, consisting of screening-only, vaccination-only, and combined vaccination and screening strategies (The details of the 38 strategies could be found in Appendix Table 1.). In line with WHO recommendations, we set screening and vaccination coverage at 70% and 90%, respectively. The screening methods included liquid-based cytology (LBC) and HPV DNA testing (e.g., Hybrid Capture 2 [HC-2]), which are recommended by Chinese guidelines, as well as Pap smears (PAP) and

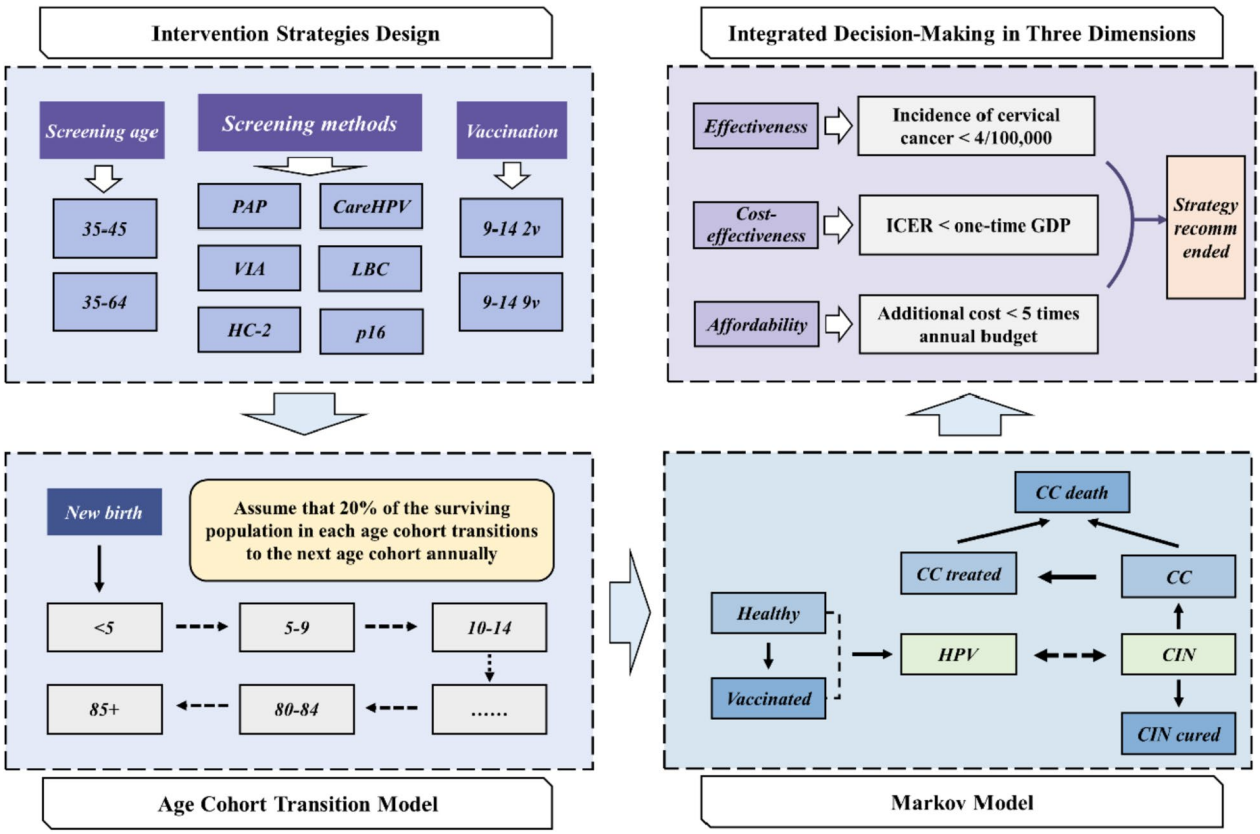

Fig. 1 Overview of study. *PAP* Papanicolaou smear (Pap smear), *VIA* visual inspection with acetic acid, *HC-2* hybrid capture 2 (HPV DNA test), *CareHPV* CareHPV test (low-cost HPV DNA test), *LBC* liquid-based cytology, *P16* p16 immunohistochemistry (biomarker for HPV-related dysplasia), *HPV* human papillomavirus, *CIN* cervical intraepithelial neoplasia, *CC* cervical cancer, *CCT* cervical cancer treated, *2v* bivalent HPV vaccine (HPV types 16 and 18), *9v* 9-valent HPV vaccine (HPV types 6, 11, 16, 18, 31, 33, 45, 52, and 58)

visual inspection with acetic acid (VIA), which are widely used in China's "Two-Cancer Screening" program (cervical cancer and breast cancer screening). We also included CareHPV and p16, which have been recommended in the U.S. Screening target populations included women aged 35–45, as recommended by the WHO, and women aged 35–64, as targeted by China's screening program. The detailed rationale for the selection of the 38 strategies is provided in Appendix Table 2 and 4.

Vaccines included domestically produced bivalent and 9-valent HPV vaccines for girls aged 9–14. Since the dosing schedule for the domestic 9-valent HPV vaccine has not yet been disclosed, we assumed it to be the same as the domestic bivalent vaccine, requiring two doses. The final efficacy of the HPV vaccines was calculated by multiplying the reported vaccine efficacy by the proportion of cervical cancer cases caused by the HPV types covered by the vaccines [20]. We assumed that vaccine protection would remain constant over the 30-year simulation period. Since clinical trials have not reported any serious adverse events related to vaccination, we did not include health impacts or costs associated with adverse events in our study [21–23].

Modelling

As shown in Fig. 1, we have developed a model comprising 18 distinct age groups, based on real population data, which simulates inter-age group mobility and predicts changes over the next 30 years. Each year, newborns (assumed to be healthy) were added to the < 5 years age group, and we assumed that 20% of individuals who did not transition between health states would move to the next age strata annually. Due to the long progression time of HPV infection to cervical cancer, a short simulation period would not adequately capture the effects of interventions. Moreover, based on current trends, achieving the WHO's targets in the short term are unlikely. Since our simulation is based on real population data, a longer simulation period would compromise the accuracy of the age structure in the model. A 30-year simulation period is therefore set to sufficiently

capture the effects of interventions while maintaining a reasonable alignment with the real population age structure.

We developed a Markov model with 9 health states: healthy, vaccinated, HPV infection, cervical intraepithelial neoplasia (CIN), CIN cured, cervical cancer (CC), CC treated, CC death, and natural death. The initial population size for each age strata, cervical cancer prevalence, age-specific cervical cancer mortality rates, and natural mortality over the next 30 years were obtained from the Global Burden of Disease (GBD) 2021 report and projections [1, 24]. Initial HPV vaccination rates (3% for ages 9–45), age-specific HPV infection rates, annual HPV clearance rates, and the proportion of CIN among HPV-infected individuals were sourced from published studies on the Chinese population [25, 26].

Since HPV is a virus that can be transmitted indirectly and affects all age groups, we assumed that all individuals could contract HPV (with a constant infection rate) [27]. Additionally, sexually active individuals aged 20–59 had an increased risk of sexual transmission (infection coefficient × 20–59 HPV infection rate). Other transition probabilities in the model were obtained from published literature (Table 1). Additionally, due to the difficulty of obtaining such a large number of transmission parameters for age-specific population structures for dynamic and microsimulation models, we chose the Markov model, which is sufficient to capture disease progression. We also employed the aforementioned HPV infection rate estimation method to account for the effects of herd immunity.

We assumed that all individuals with abnormal screening results would undergo colposcopy, and those with false positives would be excluded at this stage. However, false positives would result in a loss of quality of life. Individuals with confirmed lesions after colposcopy would undergo biopsy for diagnosis [28]. Since not all CIN cases require treatment, we assumed that 50% of detected CIN cases would be treated and would not recur during the simulation period [29]. For CC patients, we assumed that 20% would self-detect symptoms and seek treatment outside of screening. Among those treated, we assumed a 50% reduction in mortality compared to untreated patients.

All costs were adjusted to 2023 U.S. dollars (1 USD = 7.0827 CNY). Since the price of the domestic 9-valent HPV vaccine has not yet been disclosed, we estimated the cost for full vaccination of girls aged 9–14 based on the price ratio between imported and domestic bivalent HPV vaccines and the price of the imported 9-valent vaccine. Utility scores were measured in quality-adjusted life-years (QALYs), ranging from 0 (death) to 1 (perfect health). We assumed a 3% discount rate (range 0–8%) for both QALYs and costs. The range and distribution of all parameters were set based on their attributes.

To ensure model reliability, we calibrated all transition probabilities and assumed coefficients using least-squares fitting, comparing simulated HPV infection rates, the proportion of CIN among HPV-infected individuals, cervical cancer incidence, and cervical cancer-related deaths with real-world data (Appendix Fig. 1). Table 1 presents the parameters after calibration.

Effectiveness analysis

The WHO set a target of reducing cervical cancer incidence to fewer than 4 per 100,000 women by 2030[4]. However, given China's low vaccination coverage (3% for ages 9–45) and screening coverage (10–20%), the cervical cancer incidence in 2021 remained above 9 per 100,000, making this target difficult to achieve. Therefore, we used the year 2050 as the selection criterion, eliminating strategies that could not achieve this target by 2050. In addition to reporting cervical cancer incidence curves over the next 30 years, we also reported HPV infection rates and cervical cancer mortality rates under each strategy.

Cost-effectiveness analysis

The expected QALYs and costs discounted to 2024 for each strategy were obtained from the model. We calculated incremental costs and incremental QALYs for each intervention strategy compared with no intervention. We identified the cost-effectiveness frontier and calculated the incremental cost-effectiveness ratio (ICER), defined as the incremental cost per QALY gained for each strategy on the cost-effectiveness frontier compared with a lower-cost, non-dominated strategy. We used the WHO definition of cost-effectiveness (ICER < one-time GDP per capita as highly cost-effective; China's 2023 GDP per capita = US$12,614.10) and excluded strategies with an ICER greater than one-time GDP per capita compared to no intervention [36]. We would report pairwise ICERs for all strategies (Appendix Fig. 2).

Budget impact analysis

We estimated the total budget for cervical cancer prevention over the next 30 years based on the projected annual growth rate of per capita healthcare expenditure and current annual spending on cervical cancer prevention in China (approximately RMB 2 billion). Since current screening (10–20% vs. 70%) and vaccination (3% vs. 90%) coverage falls short of WHO targets, we estimated that the budget would need to increase by at least fivefold to close this gap [7]. We adopted a maximum budget affordability threshold of five times the growth trend of healthcare costs, based on previous studies, and will also conduct uncertainty analyses with multipliers ranging

Table 1 Parameters used in this study

Parameters	Base-case	Range (distribution)	References
Transition of Markov model			
Healthy			
To HPV (all age)	1.77%	± 20% (beta)	Petca (2020) [27]
To HPV (20–59)	63.49% × infection rate		HPV center (2024) [20] and model validation
HPV			
To Healthy	Age-specific	± 20% (beta)	Kang (2014) [25]
To CIN	0.30%		Zhao (2012) [26]
CIN			
To Healthy	0.03%	± 20% (beta)	Zhao (2020) [30]
To HPV	4.98%		
To CC	2.22%		
Sensitivity			
PAP	40.00%	± 20% (beta)	Zou (2020) [10]
VIA	58.00%		
HC-2	92.00%		
CareHPV	86.00%		
LBC	82.00%		
p16	91.50%		Song (2021) [31]
Specificity			
PAP	91.00%	± 20% (beta)	Zou (2020) [10]
VIA	86.00%		
HC-2	83.00%		
CareHPV	86.00%		
LBC	96.00%		
p16	71.30%		Song (2021) [31]
Effectiveness of vaccination			
2v	64.95%	± 20% (beta)	HPV center (2024) [20] and Zhu (2014) [23] and Zhu (2023) [11]
9v	92.60%		
Cost, USD			
Treatment of CIN	161.92	± 20% (gamma)	Zou (2020) [10]
Annual treatment of CC	798.00		Ding (2021) [32]
2v (full vaccination)	95.41		Menet (2024) [33]
9v (full vaccination)	213.52		
PAP	6.60		Zou (2020) [10]
VIA	2.50		
HC-2	48.60		
CareHPV	10.35		Liu (2016) [34]
LBC	26.00		Zou (2020) [10]
p16	26.00		Medical Service Price Items in Jilin Province (2024) [35]
Colposcopy	5.90		Zou (2020) [10]
Biopsy	16.40		
Utility, QALYs			
Healthy	1.00	± 20% (beta)	Zhao (2020) [30]
HPV	1.00		
CIN	0.88		
CIN cured	0.98		
CC	0.72		
CC T	0.72		
Misdiagnosis of pre-screening	− 0.001	± 20% (uniform)	Peron (2018) [28]

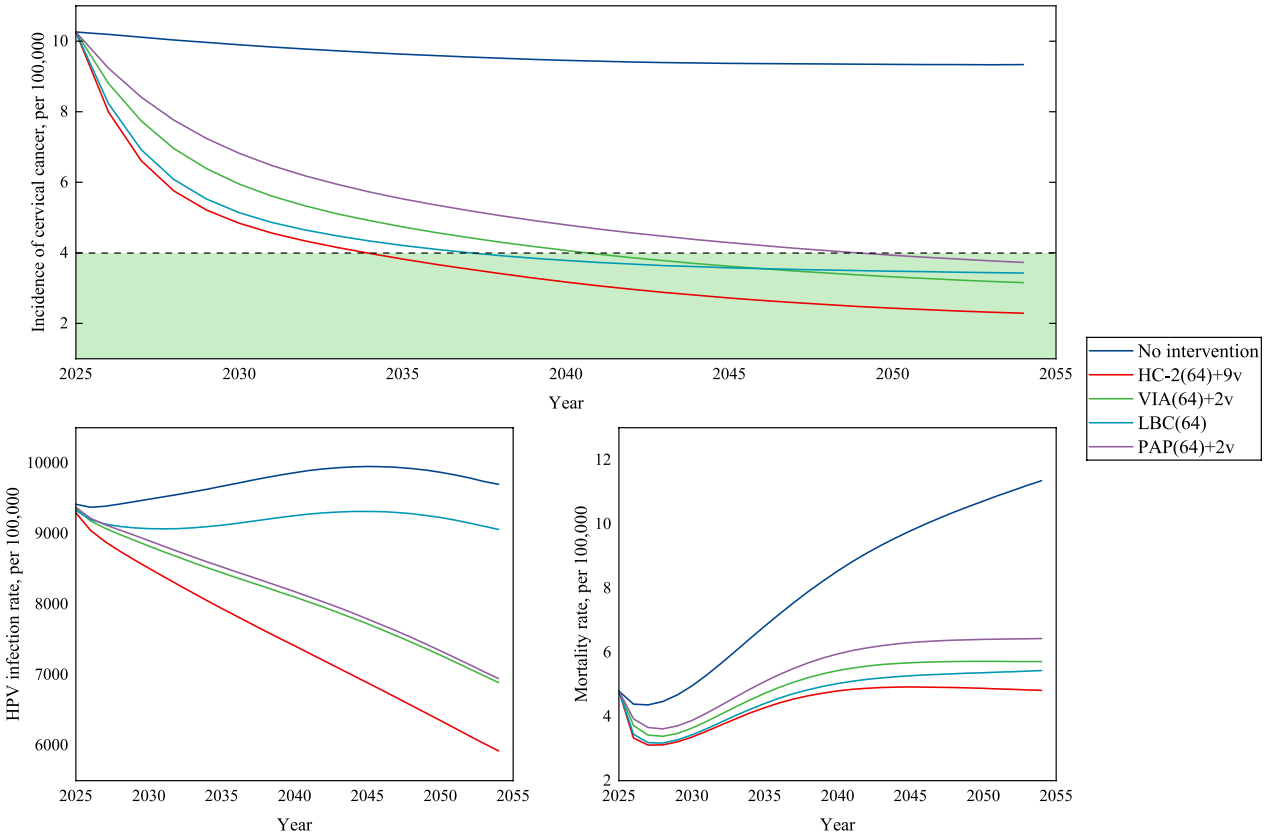

Fig. 2 Effectiveness analysis of cervical cancer prevention strategies. The number"(64)"indicates that the screening coverage age is 35–64 years. If"(64)"is not present, it refers to the age group of 35–45 years. For example, VIA (64) + 2v represents VIA screening for women aged 35–64 years combined with the bivalent HPV vaccine (2v) for girls aged 9–14 years. In addition, to better illustrate the results, we have only listed the no-intervention and the strategies mentioned earlier in the text. The timeframes for other strategies that can achieve the target effectiveness are provided in Appendix Table 3

from 3 to 8 [37]. We reported the total costs of implementing the strategies, as well as cervical cancer treatment costs, for 2025, 2035, 2045, and 2054.

Optimal strategy

We identified the final strategy that met the criteria of effectiveness, cost-effectiveness, and affordability, which would be the recommended strategy for China's national cervical cancer prevention program.

Sensitivity analysis

We performed univariate sensitivity analysis for all parameters within their respective ranges to identify the most sensitive parameters. Probabilistic sensitivity analysis was conducted using 10,000 simulations to determine the probability of each of the 38 strategies being recommended.

Additionally, given that national prevention programs could lead to price reductions due to centralized procurement of screening technologies and vaccines, we assumed a 40% price reduction to identify the optimal strategy under this scenario. We also considered budget increases ranging from 3 to 8 times the current budget to determine the recommended strategies under both constrained and expanded budget scenarios, providing more optimized options for wealthier regions in China.

Results

Effectiveness analysis

As shown in Fig. 2, 16 out of 38 intervention strategies could achieve the target of reducing cervical cancer incidence to fewer than 4 per 100,000 by 2050. The best-performing strategy, HC-2 (64) +9v, could reach the target by 2034 (3.98 per 100,000 in 2034 and 2.71 per 100,000 in 2050). The least effective strategy, PAP (64) +2v, could achieve the target by 2050 (3.94 per 100,000 in 2050).

Over the 30-year period, the most effective strategy among the 16 was HC-2 (64) +9v, which could reduce the average HPV infection rate from 9,724.21 per 100,000 (without intervention) to 7,489.86 per 100,000. The least effective was LBC (64), which could reduce the rate to 9,191.22 per 100,000. Regarding cervical cancer

mortality, the best-performing strategy was again HC-2 (64) +9v, reducing the mortality rate from 8.00 per 100,000 to 4.40 per 100,000. The least effective strategy was PAP (64) +2v, which could reduce mortality to 5.44 per 100,000.

Cost-effectiveness analysis

As shown in Fig. 3, 29 out of 38 intervention strategies had an ICER lower than 1× China's 2023 GDP per capita when compared with no intervention, indicating significant cost-effectiveness. The most cost-effective strategy was VIA, with an ICER of $1,623.98, while the least cost-effective strategy was p16 (64) +2v, with an ICER of $12,516.75.

Over the 30-year period, the additional costs compared with no intervention for the 29 cost-effective strategies ranged from $9,031,869,927.58 (VIA) to $252,723,895,839.21 (LBC [64] +9v). These strategies could yield additional QALYs ranging from 1,395,445.21 (2v) to 22,251,081.70 (LBC [64] +9v). Among these, the VIA (64) strategy was found to be the most cost-effective.

Budget impact analysis

The affordability threshold for cervical cancer prevention over the next 30 years was calculated to be $2,230,078,881.93. The budget impact analysis showed that 11 out of 38 strategies could meet this threshold (Fig. 4). These affordable strategies would require additional annual expenditures compared to no intervention, ranging from $419,938,893.25 (VIA) to $1,994,191,165.06 (VIA [64] +2v). However, they would also result in annual savings in cervical cancer treatment costs, ranging from $12,612,186.42 (2v) to $83,217,984.61 (VIA [64] +2v).

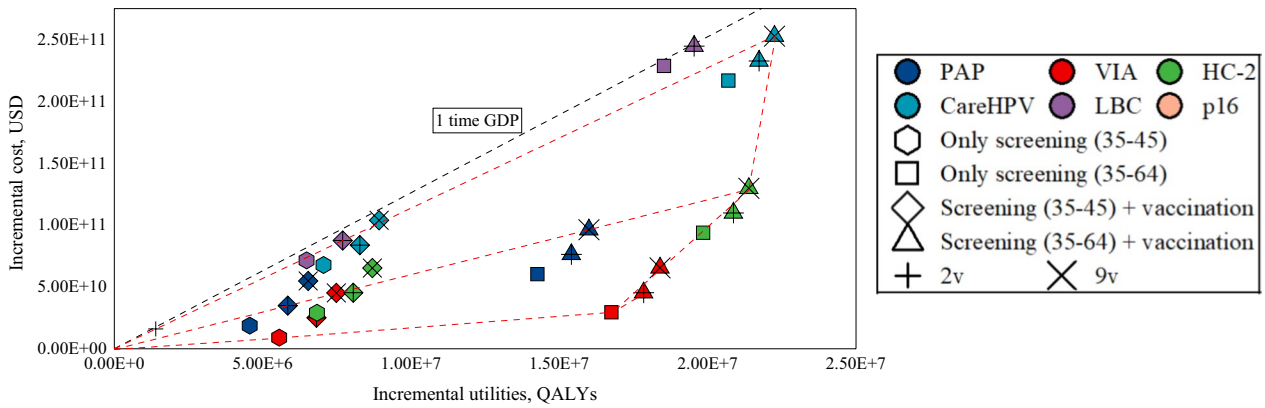

Fig. 3 Cost-effectiveness analysis of cervical cancer prevention strategies

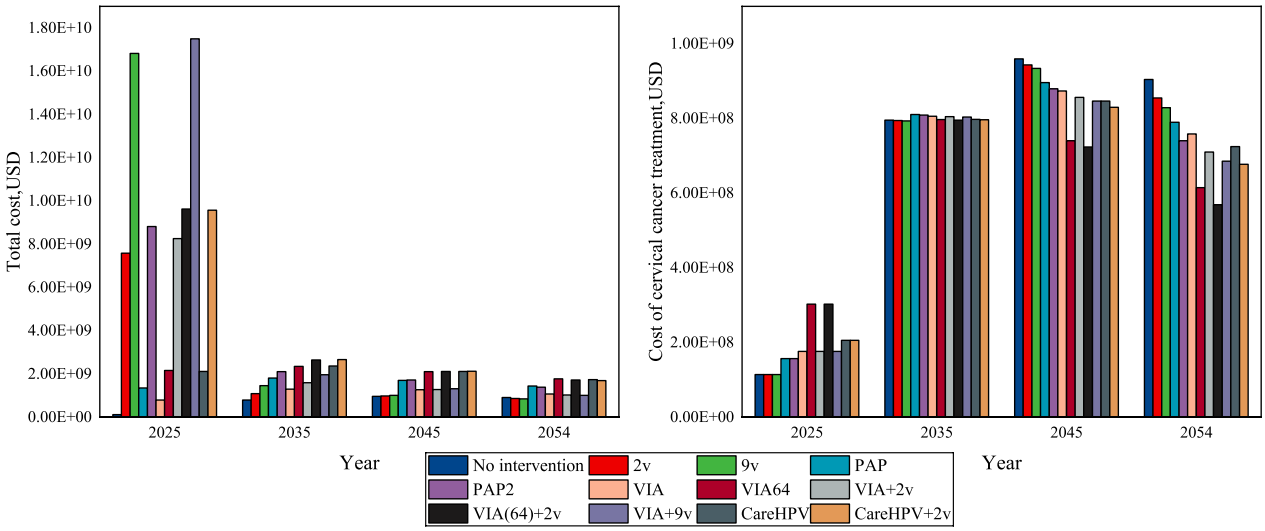

Fig. 4 Budget impact analysis of cervical cancer prevention strategies

Optimal analysis

After considering the three criteria of effectiveness, cost-effectiveness, and affordability, only the VIA (64) +2v strategy met all standards. Implementing this strategy starting in 2025 could achieve the WHO elimination target by 2041, with clear economic benefits, and would be affordable.

Sensitivity analysis

Univariate sensitivity analysis showed that the recommended strategy remained stable under most parameter variations. However, when the QALY value for cured CIN was set to its lower bound, the screening coverage to its upper bound, and the accuracy of VIA to its lower bound, no strategy met all three criteria.

Probabilistic sensitivity analysis revealed that, out of 10,000 simulations, VIA (64) +2v was recommended 7,565 times, VIA (64) +9v was recommended 455 times, VIA was recommended 12 times, and CareHPV (64) was recommended once. No other strategies were recommended.

When we considered price reductions for vaccines and screening technologies, strategies such as PAP (64) +2v, PAP (64) +9v, VIA (64) +2v, VIA (64) +9v, and CareHPV (64) were recommended. However, when we set the target to achieve the WHO goal by 2040, no strategies were recommended. Changing the cost-effectiveness threshold to 3× GDP per capita did not alter the results. When we reduced the budget to 3× the current amount, no strategies were affordable; but when we increased the budget to 8x, PAP (64) +2v, VIA (64) +2v, and VIA (64) +9v were recommended. Overall, for wealthier regions, optimization should focus on switching to CareHPV for screening and introducing the 9-valent HPV vaccine.

Discussion

Despite significant efforts in cervical cancer prevention over the past years, China has not succeeded in curbing the incidence of cervical cancer. The main reasons include a low screening coverage rate due to insufficient attention to cervical cancer, and low vaccination rates caused by limited supply and high costs. These factors have hindered the elimination of cervical cancer in China [38]. However, the calls to action by the WHO have significantly raised awareness of women's health [4], and the introduction of domestic HPV vaccines has greatly alleviated the challenges of supply and cost. Today, the primary challenge for cervical cancer prevention in China may no longer be these issues but rather the exploration of effective, cost-effective, and affordable strategies that can be implemented nationwide in a coordinated manner. With the release of China's first domestic 9-valent HPV vaccine in 2024, along with continuous advancements in cervical cancer screening technologies, we adopted a multidimensional evaluation perspective. We combined the effectiveness and cost-effectiveness targets or thresholds set by the WHO with the affordability constraints of China's current cervical cancer prevention budget to identify strategies that meet all the criteria and provide recommendations. To our knowledge, this is the first study to adopt such a novel approach and the first to evaluate the domestic 9-valent HPV vaccine in China.

Our study found that VIA (64) +2v is currently the most effective, cost-effective, and affordable strategy. Implementing this strategy could achieve the WHO cervical cancer elimination target by 2041. Screening methods such as LBC, CareHPV, and p16, which are recommended and used in the U.S. guidelines, as well as LBC and HC-2, which are recommended by Chinese guidelines, demonstrated excellent preventive effects in our study. For example, screening women aged 35–64 with HC-2, combined with vaccinating girls aged 9–14 with the 9-valent HPV vaccine, could achieve the WHO elimination target by 2034. However, these screening technologies, due to their high costs, have not been widely adopted in China's rural "Two-Cancer Screening" program without significant price reductions through centralized procurement. Similar to the combined or multiple screening strategies advocated by the guidelines, these methods have only been attempted in wealthier regions of China. Our model predicted that the additional cost required to implement the most effective strategy, HC-2 (35–64) +9v, over the next 30 years would be 9.65 times the current estimated budget, which is not affordable without substantial price reductions. Other studies on cost-effectiveness also suggest retaining VIA in regions with low willingness-to-pay (WTP), which aligns with our findings [10].

The recommended screening age group in our study is consistent with China's current national "Two-Cancer Screening" program and does not follow the WHO's recommendation of screening women aged 35–45. This is mainly because China's cervical cancer incidence rate (9.33 vs. 8.46 per 100,000) is higher than the global average, and the peak incidence occurs in women aged 35–65 [1]. Therefore, a broader screening age range is warranted to detect more precancerous lesions and cervical cancer cases.

Both WHO and China recommend vaccinating girls aged 9–14 against HPV. Our study also found that even with highly efficient screening, vaccinating girls aged 9–14 is necessary. This is already being implemented in some economically developed cities in China, such as Shenzhen and Wuxi [9]. The most direct effect of HPV vaccination is reflected in the reduction of HPV infection rates, which in turn can lower the incidence of cervical

cancer. Our study found that implementing HC-2 (64) +9v could reduce HPV infection rates to 6,352.68 per 100,000 by 2050. Since cervical cancer tends to occur in women aged 35–65, the protective effects of HPV vaccination have a delayed impact, and the 30-year simulation period we set for the study might not be enough to fully capture the health benefits in vaccinated populations. This could result in an underestimation of the vaccine's effectiveness. However, even under these conditions, we strongly recommend the vaccine. In terms of affordability, without significant price reductions, the bivalent HPV vaccine may remain the preferred vaccine for widespread immunization.

Our study's final recommendation differs from those based solely on effectiveness or economic evaluations, as we adopted more stringent selection criteria. By integrating the three thresholds of effectiveness, cost-effectiveness, and affordability, we identified VIA (64) +2v as the recommended strategy for cervical cancer prevention in most regions of China. VIA is a low-cost, simple screening method already used in resource-limited settings, and many regions have rolled out free 2-valent HPV vaccination programs, supporting its large-scale feasibility [39]. This strategy can achieve the WHO's cervical cancer elimination target, offers significant economic benefits compared to no intervention, and is affordable. Moreover, in our uncertainty analysis, this recommendation demonstrated robustness. Additionally, the price reduction scenarios and the increased affordability threshold provided new optimization directions for cervical cancer prevention in wealthier regions of China. These regions may consider replacing VIA with CareHPV, which is already part of the ongoing optimization of the "Two-Cancer Screening" program. Furthermore, they may consider switching from the bivalent HPV vaccine to the 9-valent HPV vaccine for girls aged 9–14. To facilitate national adoption of the VIA (64) +2v strategy, several coordinated policy actions may be pursued. One important approach involves the provision of fiscal subsidies to reduce financial barriers for individuals and to ease the burden on the healthcare system, thereby enhancing access to VIA screening services. In parallel, establishing favorable vaccine pricing through negotiations with manufacturers is essential to ensure the sustained affordability of the bivalent HPV vaccine, particularly in resource-constrained settings. Another key consideration is the integration of VIA screening and HPV vaccination into existing public health programs, which would enable efficient use of current infrastructure and service delivery platforms. Moreover, implementing targeted public education and awareness campaigns could play a critical role in increasing community engagement and improving the uptake of both screening and vaccination services.

Our study offers several key advantages. It employs a comprehensive design that includes nearly all recommended and feasible technologies in China, allowing for a thorough evaluation of their effectiveness in cervical cancer prevention. Using a widely adopted Markov model and real population data from 18 age groups in China, our approach provides detailed insights into long-term health and economic outcomes. Additionally, the study holds strong policy relevance by assessing effectiveness in line with WHO targets, evaluating cost-effectiveness based on WHO guidelines, and considering affordability, making it a valuable reference for both WHO goals and China's national health priorities. While our study offers innovative design and strategy recommendations, it has some limitations. First, although we considered HPV transmission, the lack of data on certain parameters, such as sexual behavior, led us to rely on simplified assumptions, which may have introduced some estimation bias. Second, we did not consider vaccination for groups outside of girls aged 9–14. Third, the screening and vaccination coverage rates were idealized based on WHO recommendations, and as a strategy evaluation study, we did not explore the feasibility of achieving these increases. Lastly, due to the memoryless assumption of Markov models and the design of the real-world strata studies, it was difficult to determine which individuals had previously been screened, making it challenging to incorporate screening intervals into our model.

In conclusion, our findings suggest that VIA (64) +2v is currently the most suitable cervical cancer prevention strategy for China. Our study emphasizes the importance of both screening and vaccination. In regions with stronger economic foundations, more accurate screening methods and the 9-valent HPV vaccine for girls could be considered. Our research provides valuable evidence for cervical cancer prevention and control policies in China and serves as a reference for many developing countries struggling with the burden of cervical cancer.

Supplementary Information

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Additional file 1.

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Author contributions
Concept and design: DCZ; Acquisition of data: YW, KZ and DZ; Analysis and interpretation of data: DCZ and DZ; Drafting of manuscripts: DCZ; Critical revision of the manuscript for important intellectual content: WT; Obtaining funding: WT. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable, this study does not involve human participants or animal subjects.

Consent for publication
All authors agreed to the publication of this manuscript.

Competing interests
The authors declare no competing interests.

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