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Evaluation of an intelligent digital platform for population management in cervical cancer screening

Xinhua Jia[1,2]*, Chen Gao[3]*, Xi'ao Da[1], Jingyi Shi[1,2], Mingyang Chen[1], Rufei Duan[4], Zhifang Li[5], Ruimei Feng[6], Yao Yang[1], Jiahuan Zhai[3], Hanyue Ding[1], Alex Ng[3], Youlin Qiao[1,2]

[1]School of Population Medicine and Public Health, Chinese Academy of Medical Sciences & Peking Union Medical College, Beijing 100730, China; [2]National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital, Chinese Academy of Medical Sciences & Peking Union Medical College, Beijing 100021, China; [3]Tencent Inclusive Health Lab, Beijing 100193, China; [4]Department of Cancer Prevention and Control, Yunnan Cancer Hospital, The Third Affiliated Hospital of Kunming Medical University, Kunming 650118, China; [5]School of Public Health, Changzhi Medical College, Changzhi 046000, China; [6]School of Public Health, Shanxi Medical University, Jinzhong 030001, China

ABSTRACT

Objective: To describe temporal changes associated with deployment of an optical character recognition (OCR)-enabled One-Identity (One-ID) digital platform for rural cervical cancer screening, focusing on over-screening rates, CIN2+ detection, colposcopy follow-up, and CIN2+ management.

Methods: A multi-county pre-post observational study was conducted in six rural counties in Shanxi, Yunnan, and Sichuan Provinces (2021–2024), encompassing 153,978 encounters. The digital platform integrates OCR identity capture, deterministic One-ID linkage, and real-time duplicate alerts. Over-screening proportions before and after digital deployment were compared, changes in CIN2+ detection rate were evaluated, and colposcopy follow-up and CIN2+ management were assessed. Differences were tested with χ^2 or Fisher's exact tests.

Results: Among 153,978 encounters, the proportion of over-screening decreased from 12.64% in 2023 to 0.17% in 2024 with an absolute reduction of 12.17% (95% CI: 11.94–12.40; $P < 0.001$). The share of women receiving a first screening within the preceding 3 y increased from 78.3% to 88.2% ($P < 0.001$). Colposcopy completion improved from 64.1% to 84.9%. The CIN2+ detection rate rose from 0.35% (2021–2023 pooled) to 0.67% in 2024 ($P < 0.001$) and CIN2+ management completion increased from 56.0% to 76.2% (95% CI: 13.3–27.2; $P < 0.001$). These improvements were consistent across age groups, counties, and screening strategies.

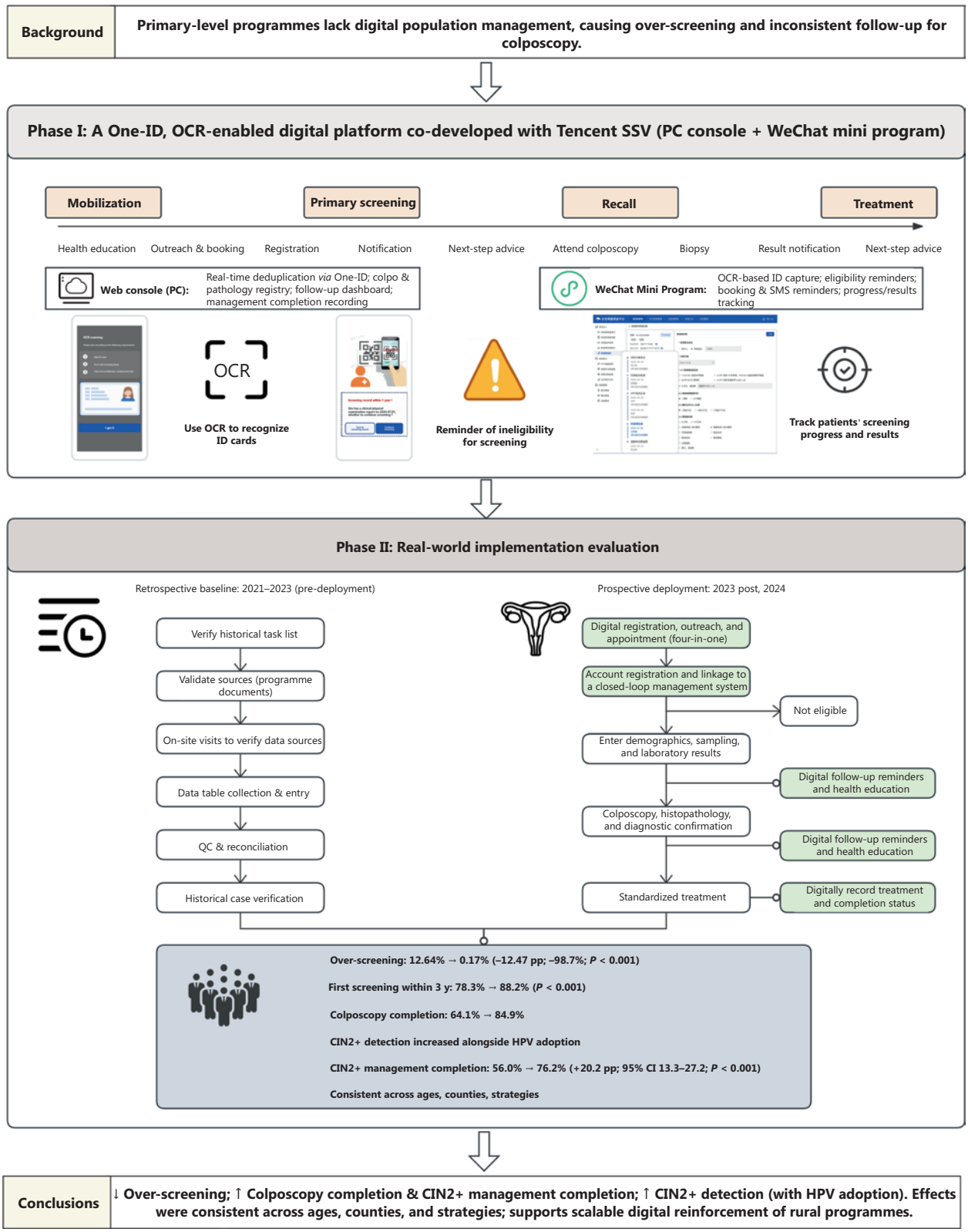
Conclusions: The OCR-enabled One-ID platform substantially reduced over-screening, increased CIN2+ detection rate, and strengthened case follow-up/management, particularly where baseline tracking was weak, supporting scalable digital reinforcement of rural screening programmes.

KEYWORDS Cervical cancer screening; digital health; population management; over-screening; rural China

Introduction

Cervical cancer is a major global public health challenge with 661,021 new cases and 348,189 deaths reported in 2022[1]. China alone accounted for nearly 22.7% of the global cervical cancer incidence and 16% of cervical cancer-related deaths[2]. The burden of cervical cancer is highly inequitable. Countries with a Human Development Index (HDI) ≤ 0.55 have twice the incidence and five times the mortality of cervical cancer compared to high-HDI settings[3,4]. To respond to this burden, the World Health Organization (WHO) released the Global Strategy to Accelerate the Elimination of Cervical Cancer as a Public Health Problem in 2020[5], which set the "90–70–90" targets to be achieved by 2030. One target requires that 70% of women 35–45 y of age undergo at least one high-quality screening. However, achieving such extensive coverage remains a formidable challenge in most regions.

*These authors contributed equally to this work.
Correspondence to: Hanyue Ding, Alex Ng and Youlin Qiao
E-mail: dinghyue@163.com, alexanderng@tencent.com and qiaoy@cicams.ac.cn
ORCID ID: https://orcid.org/0000-0001-7175-0202 and https://orcid.org/0000-0001-6380-0871
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Study Flowchart Development and real-world deployment of an optical character recognition (OCR)-enabled One-ID digital cervical cancer screening platform (web console + WeChat Mini Program). Phase I comprised system architecture design and integration of OCR to capture and standardize identity information *via* a unified national identification number (One-ID). Phase II involved implementation across six

counties with a descriptive pre-post evaluation. The end-to-end digital workflow included community outreach and appointment booking, on-site registration with eligibility verification, specimen collection, laboratory processing and result release, automated recall, colposcopy attendance, biopsy and histopathology, treatment, digital follow-up, and management completion. Over-screening (screening at intervals shorter than guideline recommendations) decreased from 12.64% to 0.17% (−12.47 percentage points; −98.7%), follow-up adherence and completion of CIN2+ management improved, and CIN2+ detection rate increased in parallel with broader adoption of HPV testing. These patterns were consistent across age groups, counties, and service delivery strategies. (This pre–post assessment was descriptive and not designed to infer causal effects). CIN2+, cervical intraepithelial neoplasia grade 2 or worse; HPV, human papillomavirus; OCR, optical character recognition; One-ID, unified national identity number; pp, percentage points; QC, quality control.

In recent years China has been attempting to expand cervical cancer screening coverage in rural areas through initiatives, such as the National Two Cancer Screening Program (NTCSP), which has provided free screening for women of eligible age since 2009. However, by 2024 only 36.8% of women nationwide had ever been screened[6], which was substantially lower than that observed in high-income countries. The disparity is particularly pronounced in rural regions, where coverage is approximately 32.3% compared to 43.2% in urban settings[6]. Major barriers include a shortage of trained personnel, limited public awareness, transportation difficulties, and challenges in patient follow-up. Fragmented data management and underdeveloped information systems further constrain the efficiency and quality of screening services[7-10]. The emergence of digital health technologies offers novel solutions to the challenges outlined above[11-14]. Evidence indicates that web- and mobile-based interventions can substantially increase participation in cervical cancer screening[15-17]. Digital platforms hold considerable promise for streamlining workflows, boosting uptake, strengthening follow-up, and providing real-time data surveillance, which are particularly valuable for screening programmes in resource-constrained areas[18,19].

In this study an intelligent population management platform for population-based cervical cancer screening was designed, deployed, and used to evaluate six counties in Shanxi, Yunnan, and Sichuan Provinces—Zezhou, Xiangyuan, Mangshi, Xinping, Yanting, and Shimian. The platform encompasses the entire screening continuum—registration, appointment booking, specimen collection, result delivery, and longitudinal follow-up, also integrates One-ID identity authentication, optical character recognition (OCR)-enabled data capture, SMS reminders, and a real-time analytics dashboard. The effectiveness in curbing over-screening, streamlining follow-up, improving CIN2+ detection rate and management was evaluated.

Materials and methods

Study design and analytical framework

A descriptive, real-world pre–post evaluation study was conducted to summarize temporal changes in over-screening, colposcopy completion, CIN2+ management, and CIN2+ detection following platform rollout without making causal claims. The study protocol was approved by the Institutional Review Board of the Chinese Academy of Medical Sciences & Peking Union Medical College (CAMS&PUMC-IEC-2025-043; CAMS&PUMC-IEC-2022-059-1). All participants provided written informed consent, and additional electronic consent was obtained for the mini-program.

Platform design and functional modules

An intelligent, web-based population management platform was developed in partnership with Tencent. It focused on population management and offered integrated services through web and a mobile mini-program. To support population-based management, the platform integrates intelligent tools built on unified individual records (One ID). A real-time check that flags any attempt to rescreen a woman before the guideline-recommended interval [3 y after a negative cytology test or 5 y after a negative high-risk HPV test and an automated follow-up queue that prioritizes women based on risk levels, e.g., human papillomavirus (HPV) 16/18 positive], enabling providers to efficiently manage daily follow-up tasks.

The platform serves the targeted women and primary care providers with multiple digital services and support flexible module reuse. From the patient perspective, the mini-program delivers screening results and follow-up recommendations in real time after physician review and allows access to personal screening history to enhance health awareness and self-management. From

the provider perspective, the mobile interface supports offline data collection, making the mobile interface suitable for outreach screening in rural areas. Data are automatically uploaded when connectivity is restored, ensuring completeness and timeliness, while reducing unnecessary patient travel.

Study population and implementation

Six sites were established across Shanxi, Yunnan, and Sichuan Provinces-Zezhou, Xiangyuan, Mangshi, Xinping, Yanting, and Shimian for the current study (**Figure 1**). All of these counties have long participated in the National Cervical Cancer Screening Program (NTCSP) and therefore have extensive experience in delivering screening services. Variations in population characteristics, screening protocols, and prior operational experience across the sites strengthen the external validity of the findings. To avoid over-screening, Zezhou, Xiangyuan, Xinping, and Yanting rotate screening activities among different townships each year and have partially implemented digital de-duplication strategies.

The study systematically collected all individual-level screening records generated before the project began (2021), including national identification numbers, screening dates, and test results. After the project was launched in 2023, digital components were integrated into the screening workflow-OCR-based registration, questionnaire administration, pelvic examination, HPV DNA testing, result notification, colposcopy, and histopathology. Records produced before 2023 serve as the baseline, reflecting the performance of pre-existing service delivery systems.

Platform evaluation

Over-screening was detected by matching national ID numbers with screening records. An individual who received a negative cytology or HPV result in 1 y but underwent screening again the following year was defined as over-screened. The digital platform captured registration details, questionnaire responses, and user-behavior metrics, including the number of notification clicks and the duration of notification viewing.

Data sources and collection

In the pre-implementation stage (January 2021-mid-2023), the NTCSP was performed in county-level maternal and child health hospitals with screening quotas assigned and confirmed by higher-level government authorities. In accordance with regulatory requirements, all participant screening records were maintained in paper form. The study team retrieved these paper archives, performed double independent manual data entry, and undertook secondary verification of aggregated counts and positive cases to ensure data quality.

Screening data from all field sites were entered directly within the clinical workflow by responsible physicians or healthcare workers and uploaded to the platform in real time in the post-implementation stage (mid-2023 onward). A One-ID together with OCR enabled automated record linkage, real-time electronic de-duplication, and end-to-end integration of screening, follow-up, and management. Follow-up and management statuses were updated in a closed loop on a single interface.

Historical (pre-implementation) records were retained in the original form and were not retrospectively subjected to electronic de-duplication; only post-implementation data underwent automated de-duplication.

Statistical analysis

Data from the platform backend were exported, including age, ID-card, screening site, screening strategy, primary screening time and results, colposcopy time, final results, recall interval, and follow-up status. Baseline characteristics and annual screening volumes were descriptively summarised. The cohort was stratified into pre- and post-digital periods, and the over-screening rate, detection rates of cervical intraepithelial neoplasia grade two or higher (CIN2+) and cervical cancer, and the follow-up completion rate among women with CIN2 plus were compared. The period-specific point estimates were reported together with the absolute delta for each outcome. The 95% confidence intervals (CIs) for the absolute delta were calculated with the Wald normal approximation. Differences in proportions between periods were tested with the Pearson Chi-squared test or Fisher exact test when any expected count was fewer than five. For multiple testing across independent comparisons of the same outcome, the Bonferroni correction was applied to control the family-wise error rate. The threshold for significance was a $P < 0.05$ in 2-sided tests. All statistical analyses were performed using R (version 4.3.1).

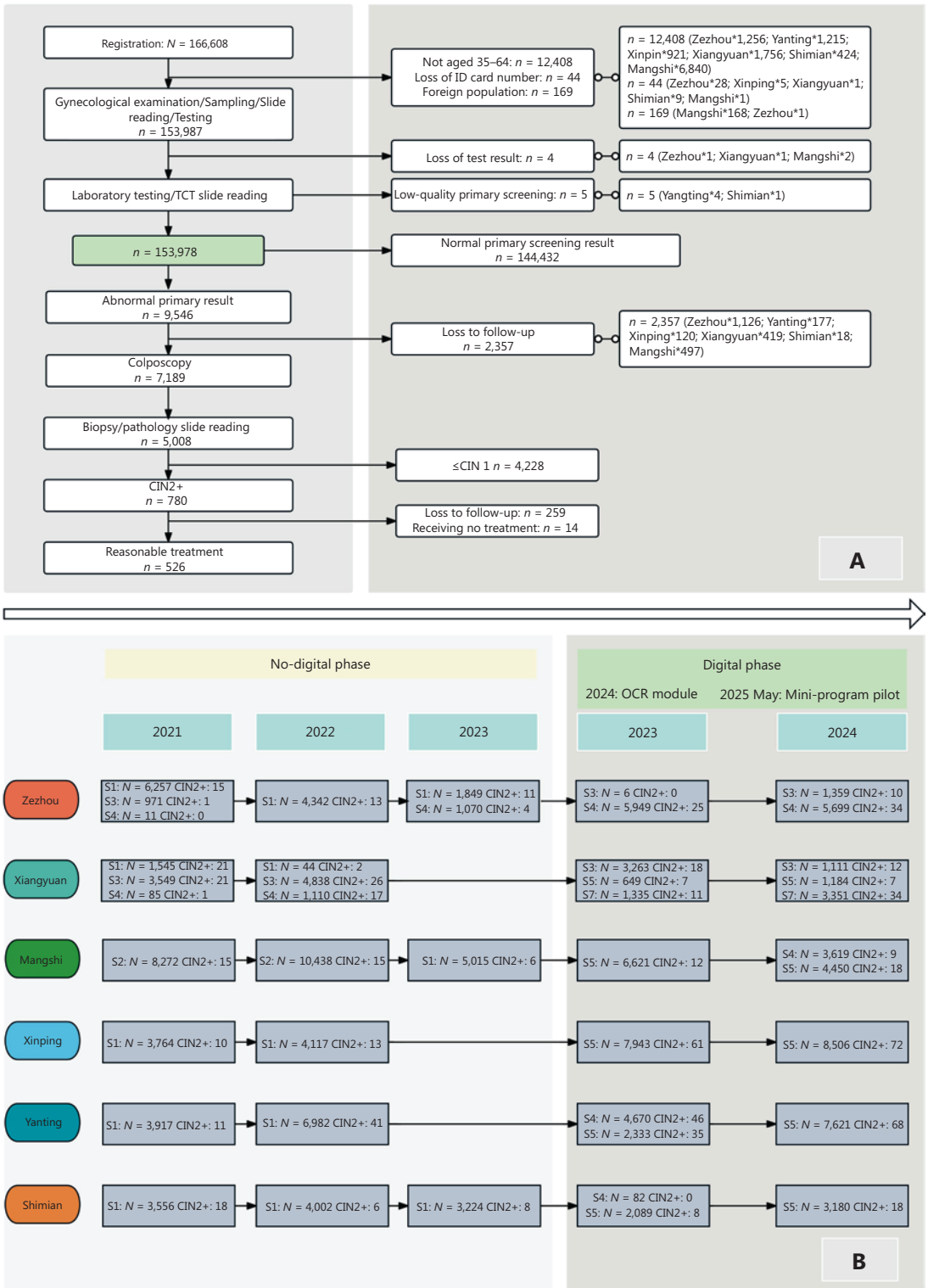


Figure 1. Participant flow and phased deployment of the digital platform across six study counties in China. (A) Participant flow for all screening encounters included in the analysis (2021–2024, combined). Boxes show the number of women at each step—from registration → primary screening → result notification → recall → colposcopy → biopsy/histopathology → CIN2+ diagnosis → treatment/management—with losses to follow-up and key exclusions displayed on the right (e.g., outside the 35–64 age range, missing ID number, lost test result,

low-quality screening). (B) Annual counts by county and study phase. The "No-digital phase" (2021–2023) reflects paper-based records, and the "Digital phase" (2024: OCR module; 2025: mini-program pilot) reflects real-time electronic capture with One-ID–based deduplication. From 2024 onward, sites predominantly adopted HPV-based primary screening; therefore, between-year CIN2+ comparisons are descriptive. Study counties: Zezhou and Xiangyuan (Shanxi), Yanting and Shimian (Sichuan), and Xinping and Mangshi (Yunnan). CIN2+, cervical intraepithelial neoplasia grade 2 or worse; HPV, human papillomavirus; OCR, optical character recognition; One-ID, unified national identity number.

Results

Baseline characteristics of screened women, 2021–2024

A total of 153,978 screening encounters were recorded from 2021 to 2024. As presented in **Table 1**, the annual volume increased from 31,927 in 2021 to a peak of 46,098 in 2023 before declining to 40,080 in 2024. Across the entire period, women 45–54 y of age constituted the largest age stratum [69,299 (45.01%)], followed by 35–44 y of age [44,550 (28.93%)], and 55–64 y of age [40,129 (26.06%)]. The proportion of women 55–64 y of age rose from 20.70% in 2021 to 31.91% in 2024, indicating a progressive reach into the upper guideline age band ($P < 0.001$). All six pilot counties contributed cases each year with Mangshi [38,415 (24.95%)] and Yanting [25,523 (16.58%)] together accounting for greater than two-fifths of total encounters. Site-level distributions differed significantly across the years ($P < 0.001$), reflecting a staggered scale-up. A marked shift in primary screening modality occurred ($P < 0.001$). Cytology-only examinations, which dominated early [19,039/31,927 (59.63%) in 2021 and 29,925/35,873 (83.42%) in 2022] declined to 10,088 (21.88%) in 2023 and 0 in 2024 as HPV-based strategies were adopted. VIA/VILI + cytology triage was confined to the initial implementation phase (2021), then replaced by HPV-based strategies. Overall test positivity (primary screening result) was 6.20% (9,546/153,978) and showed a modest year-on-year rise from 5.57% in 2021 to 6.92% in 2024 ($P < 0.001$), which was consistent with increased uptake of higher-sensitivity HPV-based strategies in later years.

OCR-enabled one-ID deduplication and reduction in over-screening

Table 2 showes the impact of real-time OCR de-duplication on cervical cancer over-screening. Following deployment of the OCR-enabled One-ID real-time de-duplication system, the over-screening proportion fell from 12.64% in 2023 to 0.17% in 2024 (single-year window), with an absolute reduction of 12.47 percentage points (pp) and a relative reduction of 98.7%. Using pooled data from 2022 to 2023 as the pre-digital comparator, the overall absolute delta was 12.17 pp (95% CI: 11.94–12.40; $P < 0.001$). By age, single-year repeat proportions declined from 14.97% to 0.18% (35–44 y), 13.34% to 0.20% (45–54 y), and 8.80% to 0.13% (55–64 y). The corresponding pooled pre-digital *vs*. 2024 absolute deltas were 15.06 pp (95% CI: 14.59–15.52), 12.55 pp (95% CI: 12.21–12.90), and 8.15 pp (95% CI: 7.77–8.53), respectively (all $P < 0.001$). The proportions fell from 1.33% to 0.33% for HPV + cytology (−1.02 pp, 95% CI: 0.79–1.25), 8.05% to 0.19% for HPV + VIA/VILI triage (−7.86 pp, 95% CI: 7.29–8.43), and 20.50% to 0.14% for HPV + cytology triage (−20.01 pp, 95% CI: 19.62–21.09) in single-year analyses. The cumulative proportion declined from 3.50% to 0.07% (−3.67 pp, 95% CI: 3.50–3.84) among counties that previously used only manual de-duplication. The cumulative proportion declined from 28.23% to 0.44% in counties without any pre-existing de-duplication. All strata converged to ≤ 0.61% (overall 0.17%) after digitalization. The proportion of women receiving a first screen within the previous 3 y increased from 78.3% in 2023 to 88.2% in 2024 ($P < 0.001$).

Improvement in colposcopy follow-up completion

The colposcopy follow-up rates increased in every age group after digitalization in age-stratified analyses (**Figure 2**). The colposcopy follow-up proportion was 59.4% among women 40–44 y of age and 69.9% among women 60–64 y of age during the paper-based phase. The age-specific rates rose to 80.4%–86.5% after digitalization, corresponding to an absolute increase of 11.8 pp in women 35–39 y of age and 23–24 pp in women 40–54 y of age. Follow-up completion rate increased from 64.1% (2820/4397) to 84.9% (4369/5149) at the population level, with an overall improvement of 20.8 pp. Inter-age variability narrowed from 10.5 pp (59.4%–69.9%) before deployment to 6.1 pp (80.4%–86.5%) after deployment.

Table 1 Characteristics of the study participants

Item	2021 (*N*, %)	2022 (*N*, %)	2023 (*N*, %)	2024 (*N*, %)	Overall (*N*, %)
Overall	31,927 (100%)	35,873 (100%)	46,098 (100%)	40,080 (100%)	153,978 (100%)
Age					
35–44	10,127 (31.72%)	10,347 (28.84%)	13,376 (29.02%)	10,700 (26.70%)	44,550 (28.93%)
45–54	15,192 (47.58%)	16,768 (46.74%)	20,750 (45.01%)	16,589 (41.39%)	69,299 (45.01%)
55–64	6,608 (20.70%)	8,758 (24.41%)	11,972 (25.97%)	12,791 (31.91%)	40,129 (26.06%)
Site					
Zezhou County	7,239 (22.67%)	4,342 (12.10%)	8,874 (19.25%)	7,058 (17.61%)	27,513 (17.87%)
Xiangyuan County	5,179 (16.22%)	5,992 (16.70%)	5,247 (11.38%)	5,646 (14.09%)	22,064 (14.33%)
Yanting County	3,917 (12.27%)	6,982 (19.46%)	7,003 (15.19%)	7,621 (19.01%)	25,523 (16.58%)
Shimian County	3,556 (11.14%)	4,002 (11.16%)	5,395 (11.70%)	3,180 (7.93%)	16,133 (10.48%)
Mangshi	8,272 (25.91%)	10,438 (29.10%)	11,636 (25.24%)	8,069 (20.13%)	38,415 (24.95%)
Xinping County	3,764 (11.79%)	4,117 (11.48%)	7,943 (17.23%)	8,506 (21.22%)	24,330 (15.80%)
Screening strategy					
HPV	4,520 (14.16%)	4,838 (13.49%)	3,269 (7.09%)	2,470 (6.16%)	15,097 (9.80%)
HPV + cytology	96 (0.30%)	1,110 (3.09%)	11,771 (25.53%)	9,318 (23.25%)	22,295 (14.48%)
VIA + cytology triage	8,272 (25.91%)	0	0	0	8,272 (5.37%)
Cytology	19,039 (59.63%)	29,925 (83.42%)	10,088 (21.88%)	0	59,052 (38.35%)
HPV + VIA/VILI triage	0	0	9,278 (20.13%)	4,667 (11.64%)	13,945 (9.06%)
HPV + cytology triage	0	0	11,692 (25.36%)	16,435 (41.01%)	28,127 (18.27%)
HPV + cytology + VIA/VILI	0	0	0	7,190 (17.94%)	7,190 (4.67%)
Primary screening result					
Positive	1,778 (5.57%)	2,203 (6.14%)	2,790 (6.05%)	2,775 (6.92%)	9,546 (6.20%)
Negative	30,149 (94.43%)	33,670 (93.86%)	43,308 (93.95%)	37,305 (93.08%)	144,432 (93.80%)
Screened in the previous year (all women)					
Yes	NA	4,721 (13.16%)	6,104 (13.24%)	1,219 (3.04%)	12,044 (9.87%)
No	NA	31,152 (86.84%)	39,994 (86.76%)	38,861 (96.96%)	110,007 (90.13%)
First-time screening within the past 3 years					
Yes	NA	NA	36,077 (78.26%)	35,364 (88.23%)	71,441 (82.89%)
No	NA	NA	10,021 (21.74%)	4,716 (11.77%)	14,737 (17.10%)

CI, confidence interval; cum, cumulative; HPV, human papillomavirus; NA, not applicable; VIA, visual inspection with acetic acid; VILI, visual inspection with Lugol's iodine; y, year.

Enhanced CIN2+ detection and case management

The overall CIN2+ detection rate increased from 0.35% in the pre-digital period (pooled 2021–2023) to 0.67% in 2024 (absolute increase 0.32 pp; 95% CI: 0.25–0.40; $P < 0.001$) (**Table 3**). The age-specific gains were consistent. Specifically, the detection rose by 0.28 pp in women 35–44 y of age (0.35% to 0.63%; 95% CI: 0.15–0.41; $P < 0.001$), 0.31 pp in women 45–54 y of age (0.29% to 0.60%; 95% CI:

Table 2 Impact of real-time OCR de-duplication on cervical cancer over-screening rates by age, screening strategy, and county cluster, 2021–2024

Item	Pre-digital (%, *n*/*N*)			Post-digital (%, *n*/*N*)	Absolute delta (%, 95% CI)[a]	*P*	Adjusted *P*[b]
	2022 (1-y)	2023 (1-y)	2023 (2-y cum)	2024 (1-y-post)			
Age							
35–44	15.57 (1,610/10,338)	14.97 (2,002/13,372)	23.18 (3,100/13,372)	0.18 (19/10,700)	15.06 (14.59, 15.52)	< 0.001[c]	< 0.001
45–54	12.03 (2,013/16,735)	13.34 (2,768/20,745)	22.15 (4,596/20,745)	0.20 (34/16,589)	12.55 (12.21, 12.90)	< 0.001[c]	< 0.001
55–64	7.57 (661/8,736)	8.80 (1,054/11,971)	16.67 (1,996/11,971)	0.13 (17/12,791)	8.15 (7.77, 8.53)	< 0.001[c]	< 0.001
Screening strategy							
HPV	6.29 (304/4,836)	3.85 (126/3,269)	12.97 (424/3,269)	0.00 (0/2,470)	5.31 (4.82, 5.79)	< 0.001	< 0.001
HPV + cytology	1.62 (18/1,110)	1.33 (156/11,769)	3.62 (426/11,769)	0.33 (31/9,318)	1.02 (0.79, 1.25)	< 0.001[c]	< 0.001
Cytology	13.27 (3,962/29,863)	23.79 (2,399/10,083)	39.21 (3,954/10,083)	NA	NA	NA	NA
HPV + VIA/VILI triage	NA	8.05 (747/9,278)	16.74 (1,553/9,278)	0.19 (9/4,667)	7.86 (7.29, 8.43)	< 0.001[c]	< 0.001
HPV + cytology triage	NA	20.50 (2,396/11,689)	28.53 (3,335/11,689)	0.14 (23/16,435)	20.36 (19.62, 21.09)	< 0.001[c]	< 0.001
HPV + cytology + VIA/VILI	NA	NA	NA	0.10 (7/7,190)	NA	NA	NA
VIA + cytology triage	NA	NA	NA	NA	NA	NA	NA
Manual de-duplication cluster							
Zezhou County	7.60 (330/4,342)	1.56 (138/8,867)	4.79 (425/8,867)	0.06 (4/7,058)	3.49 (3.17, 3.81)	< 0.001[d]	< 0.001
Xiangyuan County	5.43 (325/5,990)	2.44 (128/5,246)	8.41 (441/5,246)	0.11 (6/5,646)	3.93 (3.55, 4.30)	< 0.001[c]	< 0.001
Xinping County	5.17 (213/4,117)	9.40 (747/7,943)	19.55 (1,553/7,943)	0.12 (10/8,506)	7.84 (7.35, 8.33)	< 0.001[c]	< 0.001
Yanting County	0.06 (4/6,920)	0.04 (3/7,003)	0.07 (5/7,003)	0.01 (1/7,621)	0.04 (−0.01, 0.08)	0.274[d]	1.000
Overall	4.08 (872/21,369)	3.50 (1,016/29,059)	8.34 (2,424/29,059)	0.07 (21/28,831)	3.67 (3.50, 3.84)	< 0.001[c]	< 0.001
No de-duplication cluster							
Shimian County	18.09 (724/4,002)	31.92 (1,722/5,395)	51.07 (2,755/5,395)	0.00 (0/3,180)	26.03 (25.14, 26.92)	< 0.001[d]	< 0.001
Mangshi	25.75 (2,688/10,438)	26.53 (3,086/11,634)	38.79 (4,513/11,634)	0.61 (49/8,069)	25.55 (24.95, 26.16)	< 0.001[c]	< 0.001
Overall	23.63 (3,412/14,440)	28.23 (4,808/17,029)	42.68 (7,268/17,029)	0.44 (49/11,249)	25.69 (25.18, 26.19)	< 0.001[c]	< 0.001
Overall	11.96 (4,284/35,809)	12.64 (5,824/46,088)	21.03 (9,692/46,088)	0.17 (70/40,080)	12.17 (11.94, 12.40)	< 0.001[c]	< 0.001

*Repeat screening within the ≤ 3-year guideline interval was defined as any woman who (i) had a documented negative cervical test in the relevant look-back window and (ii) underwent screening again in the index year. The look-back windows were 1 year for 2022 (records from 2021 only) and 2023 (records from 2022 only) and 2 years for 2023 (records from 2021–2022), and 2024 (records from 2023 after digital implementation). The over-screening rates were calculated as the number of such women (numerator) divided by the total number of negative (NEG) women screened in the same index year (denominator). [a]Absolute delta was calculated as the overall over-screening rate in the pre-digital period minus that in the post-digital period. [b]Adjusted P-values were obtained using Bonferroni correction for 16 independent tests. [c]χ^2 test comparing 2024 with pooled 2021–23 counts. [d]Fisher exact test comparing 2024 with pooled 2021–23 counts due to expected cell counts < 5. CI, confidence interval; cum, cumulative; HPV, human papillomavirus; NA, not applicable; VIA, visual inspection with acetic acid; VILI, visual inspection with Lugol's iodine; y, year.

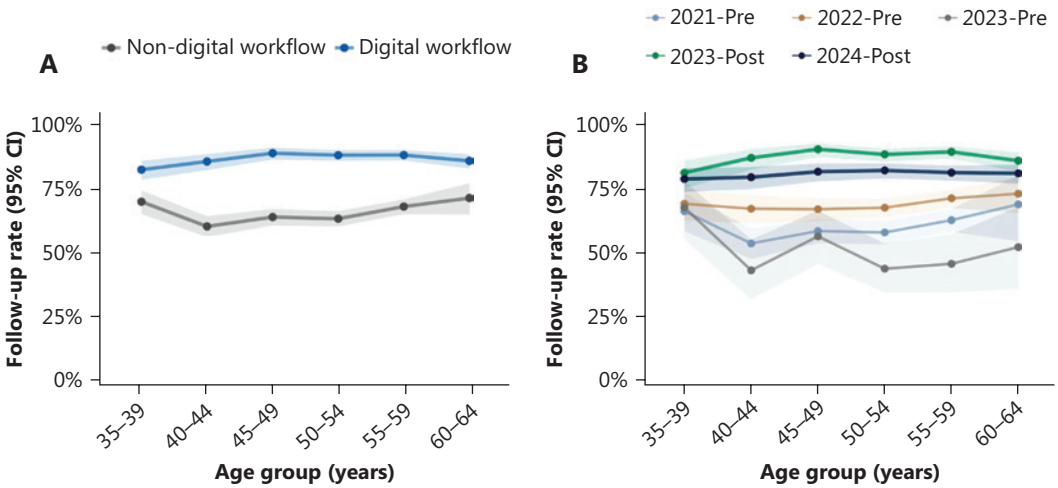


Figure 2 Digital platform implementation and age-specific follow-up rates. (A) Age-specific colposcopy follow-up completion rate before *versus* after platform roll-out, pooled across the six study counties. "Non-digital workflow" indicates paper-based management (pre-implementation) and "Digital workflow" indicates the OCR-enabled One-ID system (post-implementation). Points are the colposcopy completion proportion among women referred in the index year. Shaded ribbons show 95% binomial CIs. (B) Annual age-specific follow-up rates by study phase: 2021-Pre; 2022-Pre; 2023-Pre (pre-implementation); 2023-Post; 2024-Post (after mid-2023 roll-out and during full-year 2024 operation, respectively). From 2024 onward, sites predominantly adopted HPV-based primary screening. Thus, between-year differences are descriptive. Overall, follow-up completion rate was higher across all age groups (35–39, 40–44, 45–49, 50–54, 55–59, and 60–64 y) in the digital workflow than in the non-digital workflow. CI, confidence interval; OCR, optical character recognition; One-ID, unified national identity number; Post, post-implementation; Pre, pre-implementation.

0.20–0.41; $P < 0.001$), and 0.35 pp in women 55–64 y of age (0.46% to 0.82%; 95% CI: 0.20–0.51; $P < 0.001$). Site-level improvements were heterogeneous. Substantial increases were noted in Yanting County (0.48% to 1.02%; 0.54 pp; 95% CI: 0.33–0.75; $P < 0.001$) and Xinping County (0.29% to 0.81%; 0.52 pp; 95% CI: 0.34–0.70; $P < 0.001$) with more modest or borderline changes in Zezhou (0.30% to 0.53%; 0.23 pp; 95% CI: 0.07–0.38; $P = 0.003$) and Mangshi (0.15% to 0.27%; 0.11 pp; 95% CI: 0.02–0.21; $P = 0.014$). Xiangyuan remained stable (0.79% to 0.82%; 95% CI: −0.21 to 0.26; $P = 0.807$) and Shimian had a non-significant difference (0.30% to 0.49%; 95% CI: −0.02 to 0.40; $P = 0.059$). Primary HPV + VIA/VILI triage and multi-triage algorithms yielded CIN2+ detection rates of 0.70%–0.86% *vs.* 0.32% in pre-digital cytology-only pathways. Cervical cancer detection rate remained low and did not change materially (0.04% pre-digital *vs.* 0.04% post-digital; 95% CI: −0.02 to 0.02; $P = 0.868$), which is consistent with the relative short observation window and small absolute number of invasive cases.

Analysis of follow-up completion rate was restricted to the four sites with fully ascertained 2024 diagnostic and management outcomes (Mangshi, Shimian, Xiangyuan, and Xinping). Zezhou and Yanting were excluded because 2024 case follow-up was ongoing. Among the four sites, the proportion of CIN2+ cases (CIN2/3 or invasive cancer) achieving documented completion of the indicated diagnostic/treatment management pathway increased from 56.0% (154/275) in the pre-digital period (2021–2023) to 76.2% (385/505) in post-digital period (2023–2024), with an absolute increase of 20.2 pp (95% CI: 13.3–27.2; $P < 0.001$). Management completion of CIN2/3 patients rose from 55.6% to 76.1% (absolute increase 20.6 pp; 95% CI: 13.2–27.9; $P < 0.001$). The increase for invasive cancer (58.8% to 77.4%; absolute increase 18.6 pp; 95% CI: −3.5 to 40.7) did not reach statistical significance due to the small case count ($n = 31$). Age-specific improvements in completion rate were greatest among women 35–44 (49.4% to 84.6%; absolute increase 35.2 pp; 95% CI: 22.5–47.8; $P < 0.001$) and 45–54 y of age (50.5% to 78.9%; 28.4 pp; $P < 0.001$) with minimal change in women 55–64 y of age (68.3% to 68.5%; $P = 0.976$). Site-specific effects were large in Xiangyuan (11.4% to 95.5%; 84.1 pp; 95% CI: 76.2–92.0; $P < 0.001$) and Mangshi (16.7% to 97.4%; absolute increase 80.8 pp; 95% CI: 67.6–93.9; $P < 0.001$), modest and non-significant in Xinping (91.3% to

Table 3 Impact of digital tool on CIN2+ detection rate

	CIN2+			P^b	Adjusted P^c	Cervical cancer			P	Adjusted P^c
	Pre-digital (%, *n*/*N*)	Post-digital (%, *n*/*N*)	Absolute delta[a] (%, 95% CI)			Pre-digital (%, *n*/*N*)	Post-digital (%, *n*/*N*)	Absolute delta (%, 95% CI)		
Overall	0.35 (275/78,958)	0.67 (505/75,020)	0.32 (0.25, 0.40)	< 0.001	< 0.001	0.04 (34/78,958)	0.04 (31/75,020)	−0.00 (−0.02, 0.02)	0.868[b]	1.000
Age group										
35–44	0.35 (84/24,320)	0.63 (127/20,230)	0.28 (0.15, 0.41)	< 0.001	< 0.001	0.05 (11/24,320)	0.02 (5/20,230)	−0.02 (−0.05, 0.01)	0.255[b]	1.000
45–54	0.29 (109/36,985)	0.60 (194/32,314)	0.31 (0.20, 0.41)	< 0.001	< 0.001	0.02 (8/36,985)	0.03 (10/32,314)	0.01 (−0.02, 0.03)	0.448[b]	1.000
55–64	0.46 (82/17,653)	0.82 (184/22,476)	0.35 (0.20, 0.51)	< 0.001	< 0.001	0.08 (15/17,653)	0.07 (16/22,476)	−0.01 (−0.07, 0.04)	0.622[b]	1.000
Site										
Zezhou County	0.30 (44/14,500)	0.53 (69/13,013)	0.23 (0.07, 0.38)	0.003	0.040	0.04 (6/14,500)	0.04 (5/13,013)	−0.00 (−0.05, 0.04)	0.903[b]	1.000
Xiangyuan County	0.79 (88/11,171)	0.82 (89/10,893)	0.03 (−0.21, 0.26)	0.807	1.000	0.08 (9/11,171)	0.05 (5/10,893)	−0.03 (−0.10, 0.03)	0.307[b]	1.000
Yanting County	0.48 (52/10,899)	1.02 (149/14,624)	0.54 (0.33, 0.75)	< 0.001	< 0.001	0.06 (7/10,899)	0.02 (3/14,624)	−0.04 (−0.10, 0.01)	0.110[d]	1.000
Shimian County	0.30 (32/10,782)	0.49 (26/5,351)	0.19 (−0.02, 0.40)	0.059	0.706	0.05 (5/10,782)	0.07 (4/5,351)	0.03 (−0.06, 0.11)	0.491[d]	1.000
Mangshi	0.15 (36/23,725)	0.27 (39/14,690)	0.11 (0.02, 0.21)	0.014	0.169	0.02 (4/23,725)	0.05 (7/14,690)	0.03 (−0.01, 0.07)	0.118[d]	1.000
Xinping County	0.29 (23/7,881)	0.81 (133/16,449)	0.52 (0.34, 0.70)	< 0.001	< 0.001	0.04 (3/7,881)	0.04 (7/16,449)	0.00 (−0.05, 0.06)	1.000[d]	1.000
Strategy										
HPV	0.51 (48/9,358)	0.70 (40/5,739)	0.18 (−0.08, 0.44)	0.149	1.000	0.06 (6/9,358)	0.05 (3/5,739)	−0.01 (−0.09, 0.07)	1.000[d]	1.000
HPV + VIA/VILI Triage	NA (0/0)	0.83 (116/13,945)	NA	NA	NA	NA (0/0)	0.06 (9/13,945)	NA (0/0)	NA	NA
HPV + cytology	0.97 (22/2,276)	0.57 (114/20,019)	−0.40 (−0.81, 0.02)	0.021	0.253	0.13 (3/2,276)	0.01 (3/20,019)	−0.12 (−0.27, 0.03)	0.017[d]	0.201
HPV + cytology Triage	NA (0/0)	0.62 (173/28,127)	NA	NA	NA	NA (0/0)	0.05 (14/28,127)	NA (0/0)	NA	NA
HPV + cytology + VIA/VILI	NA (0/0)	0.86 (62/7,190)	NA	NA	NA	NA (0/0)	0.03 (2/7,190)	NA (0/0)	NA	NA
VIA + cytology Triage	0.18 (15/8,272)	NA (0/0)	NA	NA	NA	0.00 (0/8,272)	NA (0/0)	NA (0/0)	NA	NA
Cytology	0.32 (190/59,052)	NA (0/0)	NA	NA	NA	0.04 (25/59,052)	NA (0/0)	NA (0/0)	NA	NA

[a]Absolute delta was defined as the post-digital rate minus the pre-digital rate. Positive values indicate the improvement. [b]χ^2 test comparing 2024 with pooled 2021–23 counts. [c]Adjusted p-values were obtained using Bonferroni correction for 12 independent tests. [d]Fisher exact test comparing 2024 with pooled 2021–23 counts due to expected cell counts < 5. CI, confidence interval; VIA, visual inspection with acetic acid; VILI, visual inspection with Lugol's iodine.

98.5%; $P = 0.228$), and slightly negative in Shimian (96.9% to 92.3%; $P = 0.451$), suggesting a ceiling effect in which baseline manual tracking was already near-saturation.

Discussion

In this study, historical data were retrospectively collected as a control group and a digital platform was prospectively implemented as an intervention. The effectiveness of the digital population management platform in rural areas of China was evaluated by monitoring the over-screening rate, CIN2+ detection rate, and follow-up/management outcomes. Significant improvements were observed following implementation of the digital intervention across all these indicators, particularly in regions with limited-service capacity.

Impact of digital de-duplication on over-screening rates

Over- and under-screening for cervical cancer are widespread in many regions[20-26]. There is a common phenomenon in areas with limited health resources-characterized by inadequate services and poor infrastructure[3,7]. Women with health awareness undergo annual screenings, while women lacking such awareness are often entirely unfamiliar with cervical cancer screening[8,27]. This disparity highlights a major challenge in China. Despite the expanding coverage of cervical cancer screening programs, the incidence has not declined, in part due to these uneven screening practices[6,28-30]. In this study the over-screening proportions were 11.96% in 2022 and 12.64% in 2023 based on a single-year look-back. The rates of over-screening varied considerably across regions. Some areas, having already recognized the issue of over-screening, managed to keep the rate < 10% through targeted interventions. However, in the areas that lacked such awareness, the annual over-screening rate remained at approximately 25%. The 2-y cumulative over-screening rate was approximately 40%. In many regions, cytology-based screening methods were previously adopted with guidelines recommending a 3-y screening interval[30,31]. Within this interval approximately one-half of the individuals should not have undergone screening. This over-screening rate is consistent with findings reported in other studies[32]. There are many reasons for the widespread occurrence of over-screening, including cervical cancer screening providers unable to keep up with rapidly changing guidelines[33,34] or feeling pressured to meet screening quotas assigned by higher authorities[35]. The absence of individual case records made it impossible to identify repeated screenings in previous national cervical cancer screening programs[36]. Uncertainty about the timing of the last screening and fears of a missed cancer diagnosis can both lead women to request or undergo unnecessary repeat screenings[37-39]. There was a decline of over-screening proportion in all 3 age groups with the largest drop (26.18%) occurred among women 35–44 y of age. This finding may because younger women are more aware of self-health management, have more frequent access to the health care system for fertility-related tests, and have more opportunities for screening[40], thus having higher baseline repeat screening rates. Previous research had the same finding that women in the lower age group had a higher rate of repeat screening than women in the older age group[22,41]. There was also a decline in all different screening stratify groups with the largest drop (39.07%) was seen in cytology alone group. Cytology testing is a relatively traditional method among all the screening strategies. Gradual transition from cytology testing to HPV DNA testing makes the digital platform gradually being adopted, so the baseline repeat screening rate of the cytology test group was relatively high with more room for a decline. In addition, HPV DNA testing and combined screening strategies have higher sensitivity and long-term negative predictive value compared to cytology testing alone, allowing for longer screening intervals (5 y *vs.* 3 y)[25] in that case, providers with knowledge of the guidelines will direct women to choose a longer screening interval, thereby reducing the baseline repeat screening rate. In general, the de-duplication function of the digital platform is notable for reducing repeat screening under different screening strategies. Furthermore, compared to the traditional method of recording screening information through paper materials and eliminating duplications, the de-duplication effect of the digital platform has significant advantages with a reduction of 42.24% *vs.* 8.33%, indicating the OCR-enabled One-ID real-time de-duplication system on the digital platform can be a better system-level strategy that helps reduce unnecessary, repeated screening and promotes the effective use of limited medical resources[7,42].

Colposcopy follow-up, CIN2+ detection, and CIN2+ management

Management of CIN2+ individuals, including follow-up colposcopy and disease management, has long been a challenging

task at the primary care level[43,44] because the target population is often asymptomatic[35]. Follow-up in China has traditionally been performed through telephone appointments followed by examinations at hospitals or community health centers[43]. Screening recipients typically perceive screening information passively. The platform we have designed aims to address these issues by promptly delivering screening results and providing appointment channels to recipients *via* WeChat[45], as well as automatically pushing follow-up lists to healthcare providers. The unified digital platform helps prevent fragmentation of screening information and improves referral rates by documenting cases of women who require colposcopy referral due to screening abnormalities and proactively prompting healthcare providers[46,47]. The detection rate of CIN2+ increased after the implementation of the platform. This improvement appears to be driven primarily by changes in screening modalities and a reduction in over-screening, which enabled previously unscreened individuals to gradually access these services, as well as an enhanced follow-up rate that led to the identification of more lesions. This finding is consistent with previous findings in which lower rates of over-screening co-exist with higher screening adherence and the use of digital tools to systematically manage follow-up data reduces information loss and improves screening efficiency and the follow-up completion rate, making data analysis and quality control more efficient[48]. However, the relative contributions of reduced over-screening *versus* changes in screening strategy require further evaluation.

The overall management proportion for CIN2+ increased from 56.0% in the pre-digital period to 76.2% post-digital ($P < 0.001$) across these four sites with an increase of 20.6% for CIN2/3 lesions ($P < 0.001$) and 18.6% for invasive cancer (not reaching statistical significance). This finding showed that the digital platform has a promoting effect on achieving the WHO goal that 90% of women identified with cervical disease receive treatment (90% of women with pre-cancer treated and 90% of women with invasive cancer managed), especially in the period of precancerous lesions[49], which is conducive to the early prevention and control of cervical cancer. However, there was no statistically significant effect on improving the follow-up rate of invasive cancer, which may be due to the insufficient number of cases, so it is necessary to accumulate screening cases and further study the role of digital platform in the management of women diagnosed with invasive cancer.

Age-stratified gains were largest in women 35–44 y of age (35.2%) and 45–54 y of age (28.4%), while the change in the 55–64 y age group (0.2%) was negligible. This finding is consistent with age trends in data from the three U.S. health systems, which indicates that women 25–29 y of age have a higher follow-up rate for abnormal screening results than women > 40 years of age[41]. Site-specific improvements were substantial in Mangshi and Xiangyuan but not significant in Xinping and Shimian. Site heterogeneity was driven by baseline management capacity. High-performing sites showed minimal incremental benefit (ceiling effect), whereas low-performing sites realised large gains once provider task prompts and patient reminder messages were available. Challenges vary in different sites when implementing digital platform for cervical cancer control due to the burden of training, technology-specific issues, infrastructure accessibility, and technology inequality[14].

Limitations and future directions

This study had limitations. First, the non-randomized pre–post observational design limits our ability to exclude time-varying confounding (e.g., policy changes, resource infusions, outreach activities, and seasonality). Second, records from 2021 to 2023 were retrospectively collected and may include ID-entry errors or incomplete follow-up information, potentially under-ascertaining baseline over-screening. In contrast, the 2024 OCR-enabled One-ID system provided real-time de-duplication and linkage, creating asymmetric data fidelity across periods. Third, the transition from cytology to HPV-based screening can increase sensitivity, so the observed rise in CIN2+ detection rate is best interpreted as a joint effect of strategy adoption and process strengthening, rather than a platform-only effect. Overall, the improvements were contemporaneous with the platform rollout and other changes, so the platform's independent effect may be overstated. The magnitude of any indirect effects warrants investigation with longer time series.

Future research should conduct multi-center prospective studies and integrate both quantitative and qualitative methods to comprehensively assess healthcare provider experiences and cost-effectiveness. In addition, barriers faced by specific populations, such as women with low literacy, those without mobile phones, or individuals living in border regions, should be addressed through more assistive and inclusive design. For geographically expansive countries, like China, building an interoperable national digital platform is essential to reach hard-to-access or highly mobile populations. Developing

additional functionalities on this platform, such as AI-based risk assessment, is an inevitable trend. Finally, issues related to data security and quality monitoring in digital screening programs warrant urgent regulatory attention.

Conclusions

In conclusion, digital deployment of an OCR-enabled One-ID platform nearly eliminated over-screening, improved CIN2+ detection rate, and strengthen case management, especially in rural sites, suggesting a system-level data quality effect. The OCR-enabled One-ID digital platform was associated with less over-screening, higher completion of the care cascade, and greater CIN2+ detection, particularly at sites that had lower baseline performance.

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Conflict of interest statement

No potential conflicts of interest are disclosed.

Author contributions

Conceived and designed the analysis: Youlin Qiao; Alex Ng; Jiahuan Zhai; Xinhua Jia.
Collected the data: Rufei Duan; Xi'ao Da; Jingyi Shi; Zhifang Li; Ruimei Feng.
Contributed data or analysis tools: Xi'ao Da; Jingyi Shi.
Performed the analysis: Xinhua Jia.
Wrote the paper: Xinhua Jia; Chen Gao.
Critical revision of the manuscript: Youlin Qiao; Alex Ng; Jiahuan Zhai; Mingyang Chen; Yao Yang; Hanyue Ding.

Data availability statement

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study.

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