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ORIGINAL ARTICLE

Accelerating the elimination of global cervical cancer through intelligent training for colposcopy

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ABSTRACT

Objective: Cervical cancer remains a global health challenge with substantial disparities between countries. High-quality colposcopy is essential for cervical cancer prevention, yet training opportunities remain inadequate worldwide. We developed the Intelligent Digital Education Tool for Colposcopy (iDECO) to address training gaps and evaluated the effect across diverse international settings.

Methods: Six pre-post interventional training programmes were conducted in China, Mexico, and Mongolia from December 2024 to May 2025. A total of 369 trainees from 87 centers participated in a 3-week online training programme using iDECO, a bilingual web-based platform featuring authentic colposcopy cases, gamified learning pathways, and personalized analytics. The primary outcomes included colposcopy competence in general assessment, colposcopic findings, diagnostic accuracy, and management decisions. The secondary outcomes focused on participant feedback and satisfaction.

Results: Of 369 participants who completed pretests, 333 (90.24%) completed post-training assessments. Significant improvements were observed across all competency domains. Diagnostic accuracy increased with an odds ratio (OR) of 1.72 (95% CI: 1.60–1.86) with the greatest gains in high-grade lesion identification [OR = 2.27 (95% CI: 1.94–2.64)]. Squamocolumnar junction visibility and transformation zone type assessments improved with ORs of 1.41 (95% CI: 1.31–1.51) and 1.87 (95% CI: 1.73–2.01), respectively. Biopsy decision-making accuracy also showed significant improvement [OR = 2.09 (95% CI: 1.91–2.29)]. International participants showed lower baseline performance but achieved the greatest improvements. Greater than 85% of participants rated the training highly satisfactory and 83.56% preferred intelligent training over traditional methods.

Conclusions: iDECO-based training significantly improved colposcopy competence across diverse international settings with high user satisfaction. These findings support the potential for worldwide implementation of intelligent digital training tools to address colposcopy training gaps and contribute to the elimination of cervical cancer.

KEYWORDS Colposcopy; cervical cancer; intelligent training; capacity building; worldwide

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Introduction

Cervical cancer remains a significant global health challenge with > 660,000 new cases and 340,000 deaths reported worldwide in 2022[1]. Despite a well-established etiology and effective preventive measures, substantial disparities in the incidence of cervical cancer persist. Specifically, the incidence of cervical

cancer in countries with a low Human Development Index (HDI) is nearly three times higher than in nations with a very high HDI[2]. In response, the World Health Organization launched a global strategy to eliminate cervical cancer by achieving 90% vaccination, 70% screening, and 90% treatment coverage by 2030[3]. Colposcopy serves as the bridge between screening and treatment[4] with colposcopy-guided biopsy the gold standard for diagnosing cervical cancer and precancerous lesions. High-quality colposcopic assessment is essential for therapeutic decision-making and ensuring timely, appropriate care. However, colposcopy services are still lacking in many low- and middle-income countries[5]. Even where colposcopy services exist, quality often falls short due to differences in the training and expertise of colposcopists with sensitivity ranging widely from 36%–100%[6,7].

Continuous training and monitoring are essential to achieve high-performance colposcopy[8]. Nevertheless, training opportunities remain inadequate in many settings. In Africa only 12.6% of providers involved in cervical cancer prevention received prior colposcopy training[9]. In Europe formal training programmes are available in 67.7% of the member countries of the European Federation for Colposcopy with only 54.8% having oversight committees[10]. While apprenticeships in tertiary hospitals are commonly used and often effective, apprenticeships have high costs and limited accessibility. Other formats, such as continuing education programmes and academic conferences[10-12], primarily focus on theoretical knowledge, frequently lacking sufficient image-based diagnostic training and personalized guidance adapted to varying experience levels. The absence of interactive learning components and feedback mechanisms can further reduce motivation for continuous learning. Therefore, more practical training strategies suitable for worldwide implementation, especially in low-resource settings, are urgently needed.

To address these gaps in colposcopy training, our team developed the Digital Education Tool for Colposcopy (DECO), the first online colposcopy training platform in China. This platform leverages a large image database and has demonstrated promising results among Chinese trainees[13]. Building on this foundation, we created an upgraded version known as the Intelligent Digital Education Tool for Colposcopy (iDECO), which integrates personalized analytics and advanced intelligent features. However, the effectiveness and user feedback of this innovative platform require further evaluation within China and internationally. Therefore, the present study aimed to systematically assess the training effect and participant experiences with iDECO, providing broader evidence to incentivize wider implementation and potential contribution to global cervical elimination efforts.

Materials and methods

Study design and participants

This study used a pre-post interventional design to evaluate the effectiveness of iDECO-based training. Six training programmes were implemented between December 2024 and May 2025 across China, Mexico, and Mongolia (**Figure 1**). The training sessions were organized as part of an international capacity-building initiative aimed at improving colposcopy performance in diverse healthcare settings. Participants were recruited through outreach to local healthcare institutions. Investigators contacted the individuals responsible for cervical cancer screening programmes at each institution to facilitate identification and enrollment of eligible trainees. Colposcopists, gynecologists, or resident physicians who volunteered to participate were considered eligible. To ensure successful engagement with the online training platform, access to a mobile electronic device with an internet connection was required. All participants were informed of the study procedures and were expected to comply with the training and assessment components throughout the programme. No specific exclusion criteria were applied at the recruitment stage to allow for broad and inclusive participation.

Ethical approval for the study was obtained from the Institutional Review Board of the Chinese Academy of Medical Sciences and Peking Union Medical College (Approval No. CAMS & PUMC-IEC-2022-077). All participants provided informed consent prior to enrollment in the study in accordance with the ethical principles of the Declaration of Helsinki.

iDECO

The iDECO is a bilingual (Chinese and English) web-based platform that functions not only as a knowledge repository but also as an intelligent learning system designed to support the progressive development of trainees. The iDECO integrates multimodal educational content, including video lectures, digital textbooks, clinical guidelines, and explanations of terminology. The iDECO incorporates a large set of authentic colposcopy cases with time-sequence images collected from multiple clinical centers across China to enhance the practical relevance and

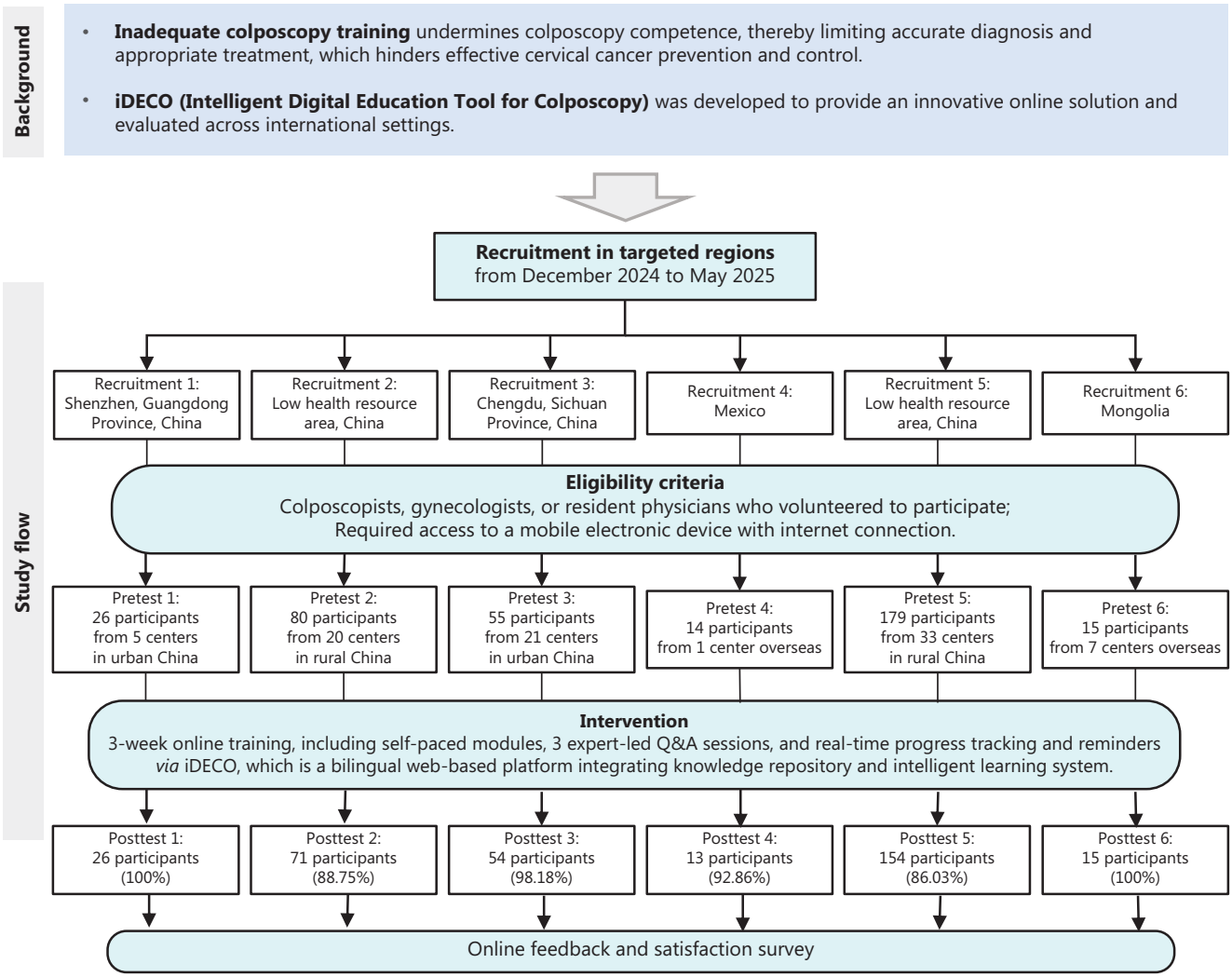


Figure 1 Continued

simulate real-world clinical scenarios. Each case was reviewed by a panel of colposcopy experts (10 experts with > 20 years of experience and 10 experts with an average of 10 years of experience) who generated standardized reports detailing general assessment, colposcopic findings, diagnoses, and management schemes. Cases with biopsies were graded according to the highest pathologic diagnosis, while cases without biopsies were assessed by expert consensus based on colposcopic findings. General assessments, colposcopic findings, and management plans were established in line with clinical guidelines.

The platform uses a gamified, closed-loop learning pathway to enhance user engagement and motivation. Upon initial login, trainees complete a self-assessment to evaluate baseline competency. The system then identifies areas of weakness, generates tailored recommendations, and intelligently assigns learning objectives. Trainees then follow a customized learning path, completing corresponding educational modules and practice tasks. Successful task completion and examination passage are rewarded with achievement badges and digital certificates. The platform continuously monitors individual learning progress through metrics, including time spent, error patterns, and development within the competency framework. A visual summary of the trainee's progress is displayed on their personal dashboard (**Figure 2**).

Study procedure

Each online training was 3 weeks in length. Participants were grouped into online learning cohorts for streamlined management prior to the training and a kickoff meeting was held

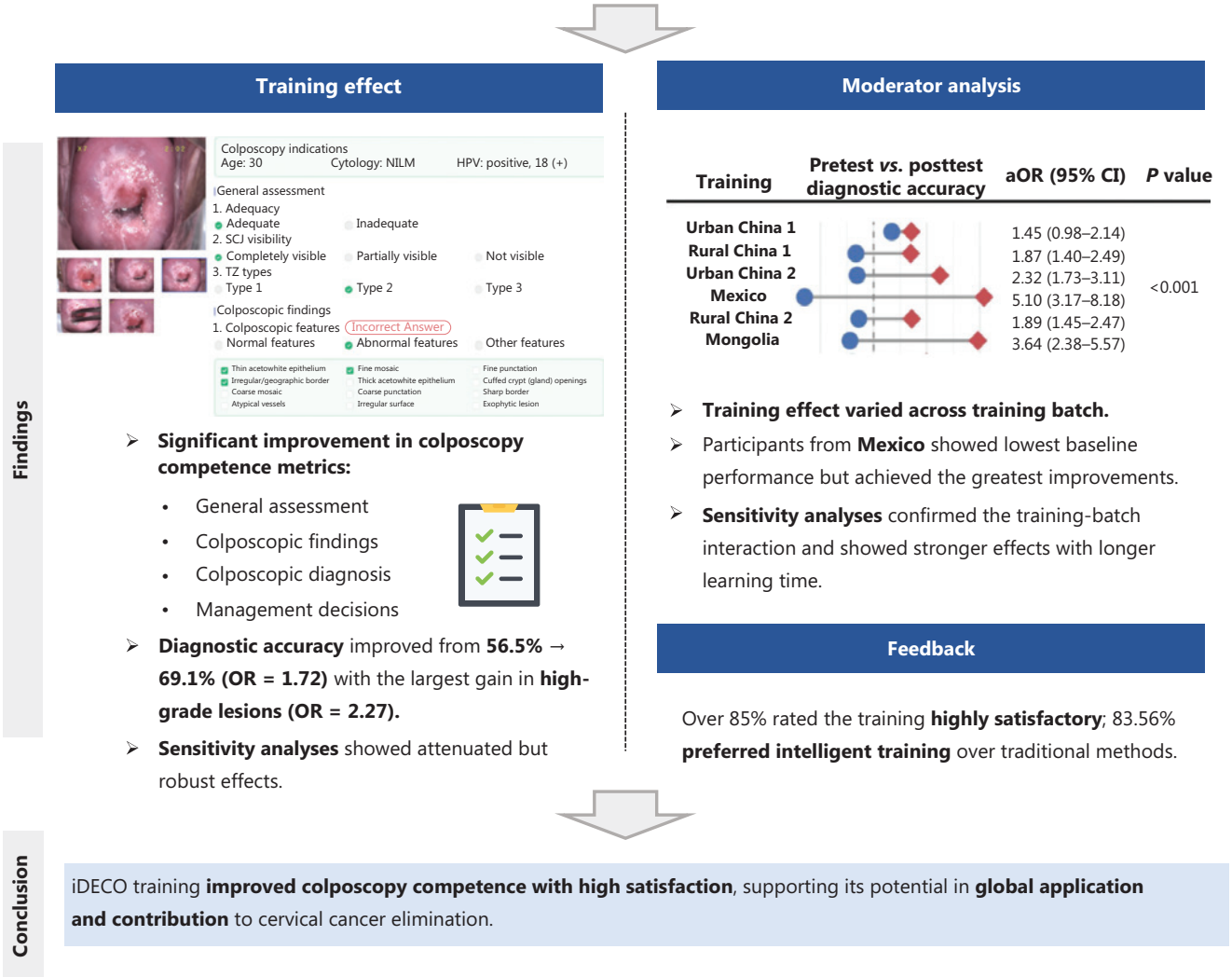


Figure 1 Study flowchart. The flowchart outlines participant recruitment and progression through a 3-week online colposcopy training programme based on the Intelligent Digital Education Tool for Colposcopy (iDECO) platform, which was offered across 6 cohorts in China, Mexico, and Mongolia. A total of 369 participants were recruited and completed a pretest from December 2024 to May 2025. After the intervention, 333 (90.2%) completed the posttest. The findings demonstrated that the training significantly improved colposcopy competence across multiple metrics. A moderator analysis showed that training effectiveness varied by cohort and participant feedback indicated high satisfaction with a strong preference for the intelligent training method over traditional ones. The study concluded that iDECO is an effective and well-received training platform with potential for global implementation to help eliminate cervical cancer. Q&A, question and answer; OR, odds ratio; aOR, adjusted odds ratio; CI, confidence interval.

to introduce the study procedures and demonstrate platform usage. Trainees were required to access the platform, provide their basic demographic and professional information, and complete a baseline competency assessment. Based on the platform feedback and recommendations, trainees then independently engaged in self-paced learning and practice modules. Throughout the training period, three live question-and-answer (Q&A) sessions were offered by experienced colposcopy experts to reinforce key concepts and clarify frequently encountered errors. The participants completed a post-training assessment and an online feedback survey at the end of each training cycle. The assessment included 18 previously unseen colposcopy cases, each presented with indications and images. Trainees were required to provide general assessments, colposcopic findings, diagnosis, and management recommendations for each case, all within a total time limit of 120 min. Trainee engagement and progress were monitored in real time by project team members, who also sent reminders



Figure 2 User interface of the Intelligent Digital Education Tool for Colposcopy (iDECO). This figure illustrates the main user interface of iDECO, a bilingual (Chinese and English) web-based platform for colposcopy training. The interface includes the following: (a) Learning Progress, displaying completion percentage for current goals and consolidation exercises; (b) Recommended Learning, providing tailored modules based on identified weaknesses; (c) Self-Assessment, showing past scores, accuracy, and access to assessment reports; (d) Stage Exercise and Knowledge Plaza, offering structured practice and access to guidelines, textbooks, and terminology; and (e) My Ability Model, a radar plot visualizing proficiency across key colposcopic competencies. The system tracks learning time, error patterns, and achievements to guide personalized training and support progress monitoring.

to ensure timely completion of learning tasks. Although all six training sessions followed the same standardized procedure, the Q&A sessions were led by different local experts in each setting, which allowed for cultural and clinical adaptations. In addition, local administrative staff supported monitoring and coordination efforts throughout the training process.

Outcomes

The primary outcome was the change in colposcopy competence from pre- to post-training. Competence was assessed through general assessment, colposcopic findings, diagnoses, and management competencies. General assessment included the identification of squamocolumnar junction (SCJ) visibility and transformation zone (TZ) type. Colposcopic findings encompassed lesion location, lesion size, thin or thick acetowhite epithelium, and vascular features. Colposcopic diagnoses were categorized as normal/benign, low-grade lesions, high-grade lesions, or suspicious for cancer. Management competence involved decisions regarding whether to perform a biopsy or endocervical curettage (ECC). In addition to overall accuracy, the accuracy of individual response categories within key variables, such as SCJ visibility, TZ type, colposcopic diagnosis, biopsy, and ECC, was also evaluated to enable a more detailed analysis. Secondary outcomes focused on participant feedback regarding the iDECO-based training, including overall satisfaction, preferred educational materials, suggestions for improvement, perceptions of intelligent training compared to traditional methods, and preferred training mode.

Statistical analysis

Sociodemographic characteristics and colposcopy experience were described separately for participants who completed the pretest and participants who completed the posttest; differences between the two groups were assessed using chi-squared tests. The performance of trainees on colposcopy competence metrics in the pre- and post-test was described using mean accuracy rates and standard deviations (SDs). The primary analysis utilized a generalized linear mixed-effect model (GLMM) with a logit link function to estimate the training effect on the competence metrics[14]. This approach appropriately handles the proportional accuracy data, the nested data structure (participants within training batches), and missing posttest data for dropouts by leveraging all available observations through a likelihood-based estimation framework. The models included time (pre- *vs.* post-training) as a fixed effect with random intercepts for training batch and individual participants. The training effect was quantified using odds ratios (ORs) with 95% confidence intervals CIs. GLMM was extended to include interaction terms between time and potential moderators (e.g., training batch, sociodemographic characteristics, work experience, and learning time) to identify factors moderating the training effect on diagnostic accuracy with the final model adjusted for all variables. In addition, separate univariate and multivariate GLMMs were used to identify factors independently associated with diagnostic accuracy at the pre- and post-test time points. A sensitivity analysis for the training effect, moderator analysis, and the posttest accuracy predictors was performed to assess the robustness of the findings against a more conservative missing data assumption. Missing posttest outcomes for participants who dropped out were imputed using the baseline-observation-carried-forward (BOCF) method for this analysis[15]. This conservative approach assumes no improvement, setting a participant's posttest performance to be identical to the pretest performance. Participant feedback on an ordinal scale was compared across geographic areas using the Kruskal-Wallis test, followed by Dunn's test with a Bonferroni correction for post-hoc pairwise comparisons. All analyses were conducted in R (version 4.5.1) with two-sided tests and a $P < 0.05$ significance threshold.

Results

Participant characteristics

A total of 369 trainees from 6 training programmes completed the pretest, as shown in **Figure 1** and **Table 1**. The trainees were recruited from 87 centers in 3 countries. Among the participants, 340 (92.14%) were from China, including 81 (23.82%) from urban areas and 259 (76.18%) from rural areas, while 14 (3.79%) were from Mexico and 15 (4.07%) from Mongolia. Most participants were 30–39 years of age [n = 135 (37.29%)], female [n = 355 (96.21%)], held a bachelor's degree [n = 272 (74.12%)], and worked in a tertiary hospital [n = 205 (56.63%)]. Of the participants, 28.62% were resident physicians, 35.69% were attending physicians, and 35.69% were associate chief or chief physicians. Nearly one-half (43.48%) of the participants had < 1 year of colposcopy experience, while 26.09% had at least 5 years of colposcopy experience. Most participants (61.52%) performed < 50 colposcopies annually. With respect to platform engagement, 25.20% spent < 5 h, 29.81% spent 5–9 h, 19.51% spent 10–14 h,

Table 1 Sociodemographics and colposcopy work experience of participants

Characteristics	Pretest (n = 369)	Posttest (n = 333)	P
Age, years			0.715
< 30	49 (13.54)	44 (13.33)	
30–39	135 (37.29)	126 (38.18)	
40–49	124 (34.25)	112 (33.94)	
≥ 50	54 (14.92)	48 (14.55)	
Gender			1.000
Male	14 (3.79)	13 (3.90)	
Female	355 (96.21)	320 (96.10)	
Area			0.004
Urban China	81 (21.95)	80 (24.02)	
Rural China	259 (70.19)	225 (67.57)	
Mexico and Mongolia	29 (7.86)	28 (8.41)	
Education level			0.048
College degree or below	29 (7.90)	23 (6.93)	
Bachelor's degree	272 (74.12)	246 (74.10)	
Master's degree or above	66 (17.98)	63 (18.97)	
Hospital level			0.816
Primary or secondary hospital	157 (43.37)	142 (43.03)	
Tertiary hospital	205 (56.63)	188 (56.97)	
Title			0.226
Resident physician	105 (28.62)	92 (27.71)	
Attending physician	131 (35.69)	123 (37.05)	
Associate chief or chief physician	131 (35.69)	117 (35.24)	
Years performing colposcopy			0.020
< 1	160 (43.48)	138 (41.44)	
1–4	112 (30.43)	102 (30.63)	
≥ 5	96 (26.09)	93 (27.93)	
Number of colposcopy examinations per year			0.022
< 50	227 (61.52)	198 (59.46)	
≥ 50	142 (38.48)	135 (40.54)	

and 25.48% spent ≥ 15 h on the training. A total of 333 trainees (90.24%) completed the posttest. Moreover, participants who completed the posttest were more likely to be from urban areas in China or from Mexico and Mongolia (P = 0.004), tended to have completed a higher level of education (P = 0.048), had longer colposcopy experience (P = 0.020), a higher case volume (P = 0.022), and greater time invested in learning (P < 0.001).

Table 1 Continued

Characteristics	Pretest (n = 369)	Posttest (n = 333)	P
Learning time			< 0.001
< 5 h	93 (25.20)	59 (17.72)	
5–9 h	110 (29.81)	108 (32.43)	
10–14 h	72 (19.51)	72 (21.62)	
≥ 15 h	94 (25.48)	94 (28.23)	

Data are presented as numbers (percentages). Totals may not sum due to missing data. Among 369 trainees who completed the pretest, 333 (90.24%) also completed the posttest. Posttest completers were more likely to be from urban China or overseas compared to non-completers and to have higher education, longer colposcopy experience, larger case volume, and greater learning time investment.

Training effect on general assessment and colposcopy findings

The mean accuracy of SCJ visibility assessment increased from 54.89% (SD = 14.06%) at pretest to 62.97% (SD = 14.21%) after training [OR = 1.41 (95% CI: 1.31–1.51), $P < 0.001$], as shown in **Table 2**. Accuracy improved across all levels of SCJ visibility. Cases with a partially visible SCJ had the lowest baseline accuracy (37.46%) and the smallest improvement [OR = 1.29 (95% CI: 1.12–1.47)], whereas cases with a completely visible SCJ had the highest initial accuracy (64.82%) and the greatest improvement [OR = 1.67 (95% CI: 1.48–1.88); both $P < 0.001$]. The accuracy for TZ type identification rose from 52.66% (SD = 17.80%) to 67.54% (SD = 16.24%) [OR = 1.87 (95% CI: 1.73–2.01), $P < 0.001$]. Type 1 TZ cases had the highest accuracy in pretests (69.73%) and posttests (77.16%), while type 3 TZ cases had the lowest pretest accuracy (41.98%) but the largest gain [OR = 2.58 (95% CI: 2.32–2.88), $P < 0.001$]. The training effect was strong for identifying lesion characteristics. The probability of correct identification was nearly three-fold higher for lesion location [OR = 2.94 (95% CI: 2.68–3.23)] and thin acetowhite epithelium [OR = 3.04 (95% CI: 2.71–3.41); both $P < 0.001$]. Significant gains were also shown for lesion size [OR = 1.73 (95% CI: 1.59–1.89)], thick acetowhite epithelium [OR = 1.67 (95% CI: 1.42–1.95)], and vascular features [OR = 1.75 (95% CI: 1.53–2.00); all $P < 0.001$].

Training effect on diagnostic accuracy and management decisions

Overall colposcopic diagnostic accuracy improved from 56.53% (SD = 14.12%) to 69.08% (SD = 14.55%), corresponding to a 1.72-fold higher likelihood of a correct diagnosis after training [OR = 1.72 (95% CI: 1.60–1.86), $P < 0.001$; **Table 2**]. The diagnostic accuracy was highest for suspicious cancer (84.40%) and lowest for high-grade lesions (48.15%) in the pretest. Despite this low baseline, high-grade lesions had the greatest improvement [OR = 2.27 (95% CI: 1.94–2.64)], followed by low-grade lesions [OR = 2.18 (95% CI: 1.95–2.44); both $P < 0.001$]. Conversely, the accuracy for normal/benign cases remained unchanged [OR = 0.92 (95% CI: 0.78–1.09), $P = 0.339$] and the improvement for suspicious cancer did not reach significance [OR = 1.90 (95% CI: 0.98–3.67), $P = 0.058$]. Management decision-making also improved markedly. The probability of correct decisions increased for biopsy [OR = 2.09 (95% CI: 1.91–2.29)] and ECC [OR = 2.35 (95% CI: 2.18–2.53); both $P < 0.001$]. Accuracy in identifying cases requiring biopsy [OR = 3.70 (95% CI: 3.28–4.18)] and ECC [OR = 3.90 (95% CI: 3.53–4.31); both $P < 0.001$] improved substantially. However, accuracy in withholding biopsy declined [OR = 0.78 (95% CI: 0.66–0.92), $P = 0.003$], while accuracy in withholding ECC showed no significant change [OR = 0.94 (95% CI: 0.80–1.10), $P = 0.425$]. Sensitivity analyses of the training effect showed slightly attenuated effect sizes but the main conclusions remained unchanged (**Table S1**).

Moderators of the training effect on diagnostic accuracy

Diagnostic accuracies in the pre- and post-test across participant subgroups are presented in **Figure 3** and **Table S2**. Univariate analyses indicated that diagnostic accuracy varied across training batches in the pretest and was higher among participants with a higher professional title, more years of colposcopy experience, and greater annual colposcopy volume. Only training batch [Mexico *vs*. the first training in urban China: adjusted OR (aOR) = 0.59 (95% CI: 0.40–0.87)] and professional title [associate chief/chief *vs*. resident physician:

Table 2 Effect of training on colposcopy competence metrics

	Pretest mean (SD), %	Posttest mean (SD), %	OR (95% CI)	*P*
SCJ visibility	54.89 (14.06)	62.97 (14.21)	1.41 (1.31, 1.51)	< 0.001
Completely visible	64.82 (24.70)	74.80 (22.21)	1.67 (1.48, 1.88)	< 0.001
Partially visible	37.46 (26.51)	43.55 (27.43)	1.29 (1.12, 1.47)	< 0.001
Not visible	57.55 (33.59)	64.45 (29.49)	1.41 (1.19, 1.67)	< 0.001
TZ types	52.66 (17.80)	67.54 (16.24)	1.87 (1.73, 2.01)	< 0.001
Type 1	69.73 (31.11)	77.16 (25.18)	1.50 (1.28, 1.76)	< 0.001
Type 2	55.37 (36.08)	61.00 (36.28)	1.33 (1.10, 1.60)	0.003
Type 3	41.98 (23.60)	63.81 (24.03)	2.58 (2.32, 2.88)	< 0.001
Lesion location*	57.75 (22.38)	79.11 (15.26)	2.94 (2.68, 3.23)	< 0.001
Lesion size*	29.50 (15.24)	41.56 (18.32)	1.73 (1.59, 1.89)	< 0.001
Thin acetowhite epithelium*	44.32 (27.92)	67.41 (25.91)	3.04 (2.71, 3.41)	< 0.001
Thick acetowhite epithelium*	57.53 (30.68)	69.00 (25.36)	1.67 (1.42, 1.95)	< 0.001
Vascular features*	29.79 (23.22)	42.09 (25.39)	1.75 (1.53, 2.00)	< 0.001
Colposcopic diagnosis	56.53 (14.12)	69.08 (14.55)	1.72 (1.60, 1.86)	< 0.001
Normal/benign	64.58 (30.69)	63.29 (28.61)	0.92 (0.78, 1.09)	0.339
Low grade	55.46 (24.55)	71.38 (23.32)	2.18 (1.95, 2.44)	< 0.001
High grade	48.15 (28.29)	66.92 (25.83)	2.27 (1.94, 2.64)	< 0.001
Suspicious cancer	84.40 (34.70)	90.56 (27.56)	1.90 (0.98, 3.67)	0.058
Biopsy	72.04 (16.01)	84.28 (10.80)	2.09 (1.91, 2.29)	< 0.001
Yes	72.59 (22.78)	89.64 (13.88)	3.70 (3.28, 4.18)	< 0.001
No	70.29 (28.59)	65.54 (27.66)	0.78 (0.66, 0.92)	0.003
ECC	49.24 (17.17)	69.03 (16.76)	2.35 (2.18, 2.53)	< 0.001
Yes	38.93 (27.95)	67.27 (23.81)	3.90 (3.53, 4.31)	< 0.001
No	74.97 (28.48)	72.65 (27.31)	0.94 (0.80, 1.10)	0.425

Data are presented as the mean (SD) of accuracy rates (%). Training effects were estimated using a generalized linear mixed-effects model (GLMM) with a logit link, accounting for the nested structure of participants within training batches and leveraging all available data, including dropouts. Time (pre- *vs*. post-training) was modeled as a fixed effect with random intercepts for training batch and individual participants. Training effects are reported as odds ratios (ORs) with 95% confidence intervals (CIs), reflecting the multiplicative change in the probability of a correct response after training. *Analysis for these indicators was restricted to cases with abnormal colposcopic findings. SD, standard deviation; OR, odds ratio; CI, confidence interval; SCJ, squamocolumnar junction; TZ, transformation zone; ECC, endocervical curettage

aOR = 1.23 (95% CI: 1.00–1.51)] remained statistically significant predictors on multivariate analysis. For the posttest, Multivariate analysis showed that diagnostic accuracy differed among training batches and was positively associated with more years of colposcopy experience [1–4 y *vs*. < 1 y: aOR = 1.23 (95% CI: 1.01–1.50)] and longer learning time [10–14 h *vs*. < 5 h: aOR = 1.29 (95% CI: 1.01–1.64); ≥ 15 h *vs*. < 5 h: aOR = 1.34 (95% CI: 1.05–1.70)] for the posttest. Sensitivity analyses of the posttest diagnostic accuracy produced consistent results (**Table S2**).

Figure 3 (right panel) presents the results of the multivariate analysis testing for interaction effects. A significant interaction was observed between training effect and training batch in the primary analysis (*P* for interaction < 0.001) with aORs ranging

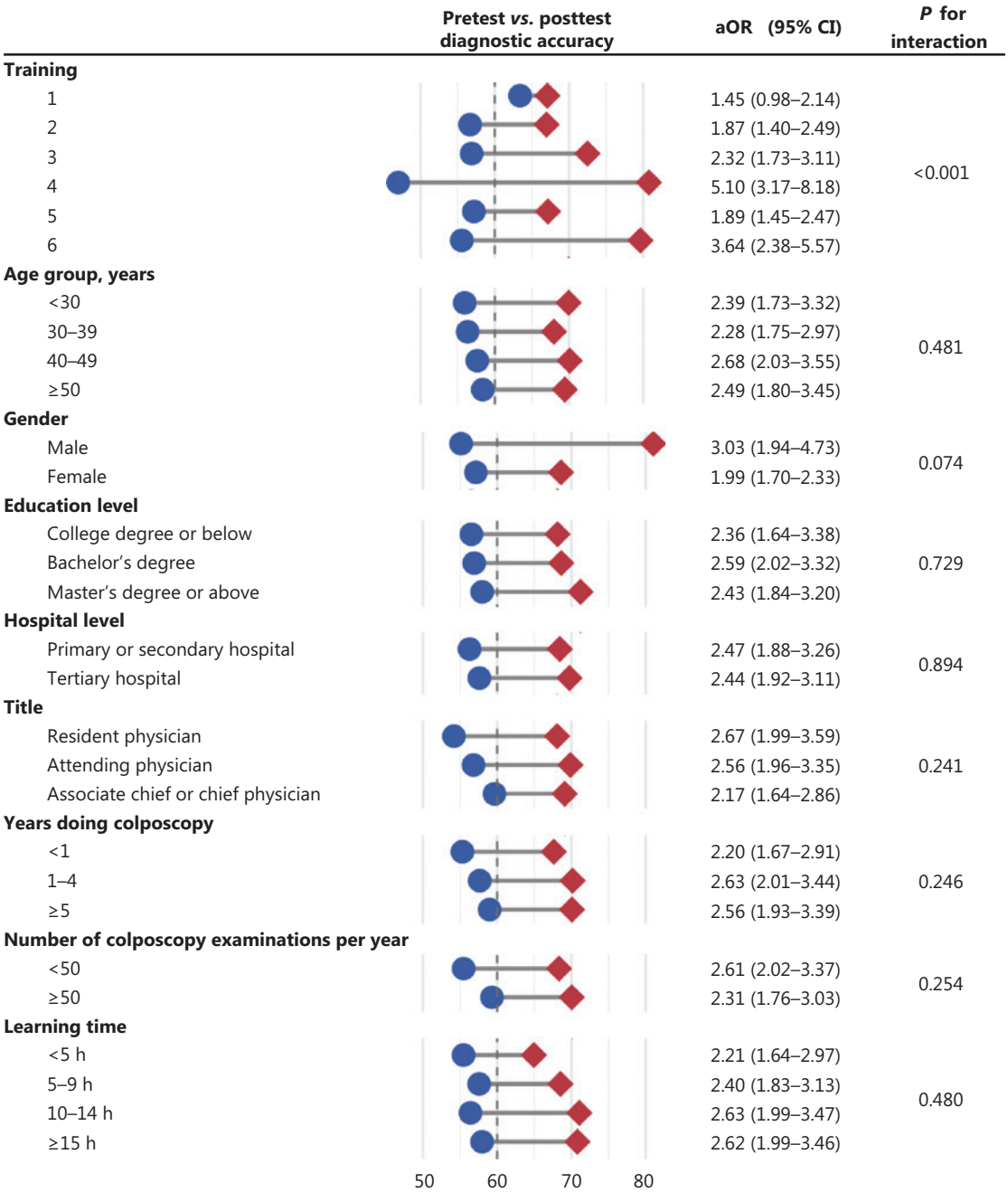


Figure 3 Moderators of the training effect on diagnostic accuracy. This figure illustrates factors moderating the training effect on diagnostic accuracy. A generalized linear mixed-effects model (GLMM) with interaction terms between time (pre- *vs.* post-training) and potential moderators was used, adjusting for all variables shown. **Left panel:** Dumbbell plot showing mean diagnostic accuracy changes from pretest (blue circles) to posttest (red diamonds) for each subgroup. **Right panel:** Adjusted odds ratios (aORs) represent the training effect for each subgroup relative to its reference group after controlling for other variables. *P* for interaction tests whether the training effect differs significantly across moderator levels. An aOR > 1 indicates a greater training benefit. aOR, adjusted odds ratio; CI, confidence interval.

from 1.45 (95% CI: 0.98–2.14) in the first cohort to 5.10 (95% CI: 3.17–8.18) in the fourth cohort. Sensitivity analyses confirmed the interaction with training batch (*P* for interaction < 0.001) and identified a significant interaction with learning time (*P* for interaction = 0.021, **Table S3**). Training gains generally increased with longer engagement and the aOR rising

from 1.87 (95% CI: 1.42–2.46) in the < 5 h group to 2.60 (95% CI: 1.99–3.41) in the 10–14 h group in the sensitivity analyses. No other variables showed significant interactions with the training effect in primary or sensitivity analyses.

Training feedback and satisfaction

A total of 314 (85.09%) participants completed the feedback questionnaire (**Figure 4**). Most participants gave the highest rating (score of 5) for the iDECO-based training, as follows: fit with personal needs (74.52%); helpfulness for clinical work (83.76%); willingness to recommend (82.17%); willingness to continue using the platform (84.39%); and overall satisfaction (85.35%). Regional differences were detected in participants' willingness to recommend ($P = 0.008$, **Figure S1**), with trainees from urban China reporting higher scores than trainees from rural China (Bonferroni-adjusted $P = 0.008$). Video courses were the most favored educational materials (89.81%), followed by online Q&A sessions (75.48%) and image interpretation exercises (71.34%); books and guidelines were the least preferred educational materials (55.73%). Of the participants, 77.07% recommended incorporating virtual simulations, such as virtual reality (VR) or augmented reality (AR), while 69.75% of the participants suggested adding more professional content and expert-led Q&A sessions to improve the programme. Peer experience sharing was selected by only 50.64% of the participants. Among the 46.50% of participants who had prior colposcopy training experience, most perceived the intelligent training to be more authoritative (81.51%), practical (86.30%), intelligent (88.36%), engaging (78.08%), and convenient (78.08%) compared to traditional approaches; 83.56% preferred the intelligent training overall.

Discussion

Main findings

Six training programmes were administered utilizing the iDECO in China, Mexico, and Mongolia, demonstrating effectiveness in improving colposcopy competence across diverse populations. Significant gains were observed in multiple domains, including general assessment, identification of colposcopic findings, diagnostic accuracy, and biopsy decision-making capabilities. Baseline diagnostic accuracy was associated with trainee characteristics, while improvements in accuracy were moderated by training cohort. Although participants responded positively to this intelligent training approach, regional differences were notable. These findings highlight the potential of iDECO for worldwide implementation, although successful deployment requires careful cultural adaptation and contextualization to local healthcare environments.

iDECO: an integrated platform for training and assessment

The iDECO serves as an effective assessment tool for evaluating trainee competencies and a practical training instrument for skill enhancement. Despite variations in participant characteristics, case complexity, and severity classifications, baseline diagnostic accuracy remained comparable to findings in our previous study[13]. Moreover, baseline performance correlated positively with professional title and colposcopy experience, underscoring the ability of the platform to discriminate actual clinical competence. Importantly, all subgroups of trainees demonstrated significant improvement after training. The magnitude of the training effect was not moderated by professional title or years of experience, indicating that the programme is broadly effective across different levels of prior expertise. This generalizability suggests that the training can benefit providers, regardless of baseline proficiency and may be particularly valuable in low-resource settings where clinical exposure and formal training opportunities are limited[16]. Given the lack of standardized certification mechanisms for colposcopy in many settings, the iDECO, which combines assessment, training, and certification, provides a one-stop solution to support competency evaluation and professional accreditation. This integrated approach may ultimately contribute to more equitable workforce development and sustained quality assurance in cervical cancer screening.

Improved accuracy in high-grade lesion identification

Overall diagnostic accuracy improved significantly after training with the most substantial gains observed in identifying high-grade lesions. Accurate differentiation between low-and high-grade lesions is essential because high-grade lesions mark the threshold for treatment, whereas low-grade lesions are generally monitored through follow-up evaluations[17]. Expert consensus recommends a minimum concordance rate of 65% between colposcopic impression and pathologic diagnosis for high-grade lesions[18]. However, the pretest results

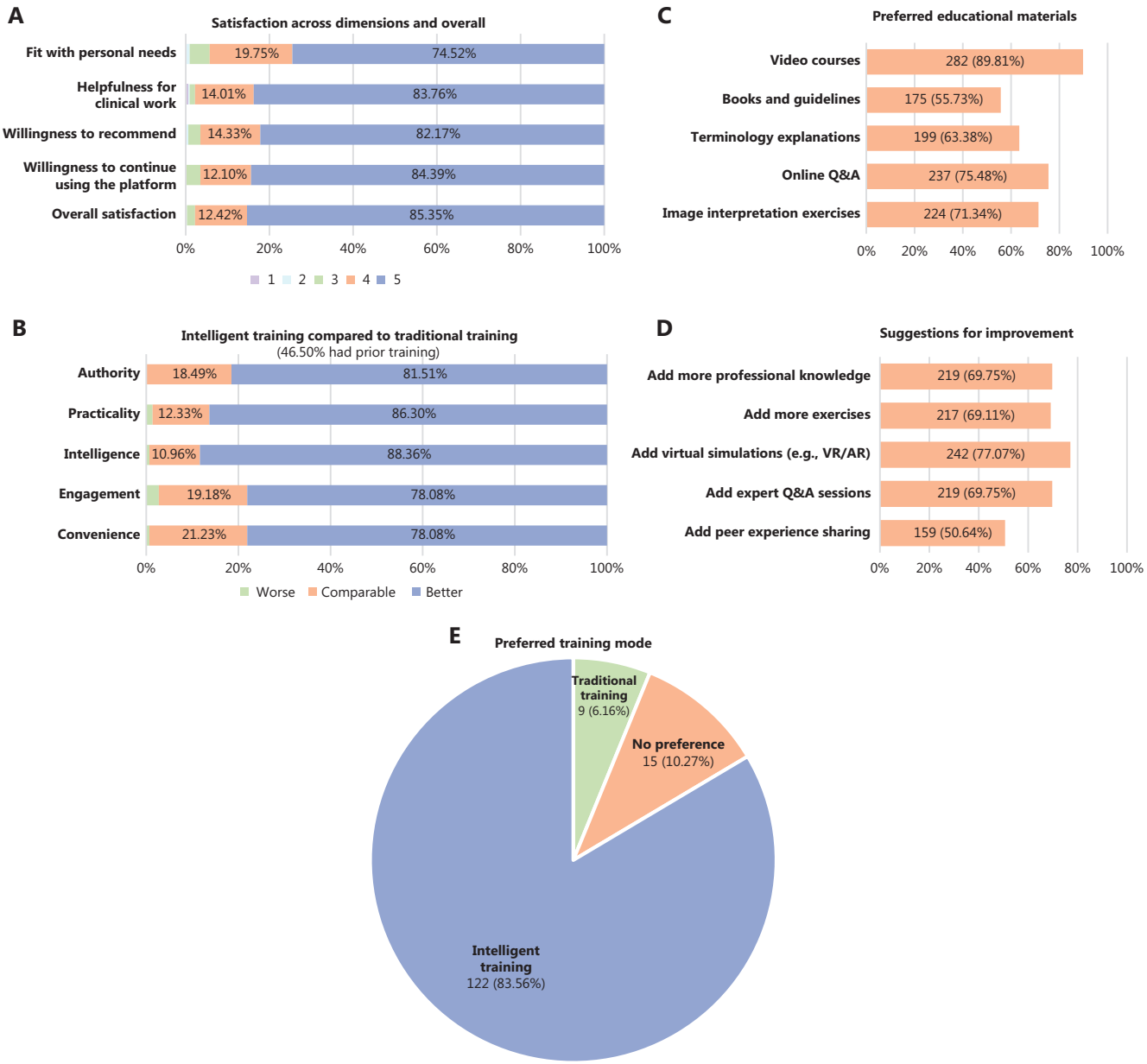


Figure 4 Feedback on the training. This figure summarizes participant feedback on the intelligent colposcopy training programme. A total of 314 trainees completed the feedback questionnaire. (A) Satisfaction across dimensions and overall; (B) perception of intelligent training compared to traditional training; (C) preferred educational materials; (D) suggestions for improvement; (E) preferred training mode. Q&A, question and answer; VR, virtual reality; AR, augmented reality.

revealed a diagnostic accuracy of only 48% for high-grade lesions, which was nearly one-half that achieved for suspicious cancer cases. This deficiency was associated with inadequate identification of key abnormal features with accuracy rates of 44% and 57% for thin and thick acetowhite epithelium, respectively. Unlike the more apparent manifestations of cancer, such as exophytic lesions, acetowhite changes and vascular abnormalities require extensive case-based practice to master[19]. The iDECO addresses this challenge by providing the correct diagnosis and clarifying the reasoning process through annotated time-sequence images that illustrate the dynamic progression of lesion features. However, the diagnostic utility of certain features remains limited. The analysis revealed low interobserver agreement on vascular patterns among experts

and identification of vascular features remained suboptimal despite improvements following training. This aligns with previous studies showing that while acetowhite epithelium remains an important diagnostic feature, mosaic and punctation patterns, though highly specific, tend to have lower sensitivity due to infrequent occurrence[20]. With HPV vaccination and HPV-based primary screening altering the epidemiology profile and reducing the visibility of classic lesion patterns[21-24], the development of new diagnostic markers that remain effective under these changing conditions has become increasingly important.

Challenges in overdiagnosis and biopsy decision-making

Notably, no improvement in diagnostic accuracy was observed for normal or benign cases, reflecting a tendency toward overdiagnosis, a conservative pattern also evident in biopsy practices. This finding may partly reflect the inherent difficulty in distinguishing normal cervical tissue from minor abnormalities, particularly subtle metaplasia or thin acetowhite epithelium. To minimize missed diagnoses, current guidelines from the American Society of Colposcopy and Cervical Pathology (ASCCP) recommend multiple targeted biopsies of all areas showing acetowhitening, metaplasia, or more severe abnormalities[4]. While this approach improves detection, unnecessary procedures inevitably occurs in cases in which tissue sampling is unwarranted. This more aggressive clinical approach, marked by overdiagnosis, excessive biopsies, and even overtreatment in ambiguous cases, often becomes the default to avoid medicolegal risk, particularly when colposcopists lack adequate training or confidence in their diagnostic abilities[25,26]. However, this approach represents a clinical compromise rather than an optimal solution because the physical, psychological, and financial burdens on patients cannot be overlooked[27]. In addition to enhanced training initiatives, implementing risk-stratified strategies that incorporate prior screening history and HPV vaccination status could help optimize patient care. Emerging biomarkers, such as p16 immunostaining and Ki-67 proliferation, show promise for predicting high-grade lesion progression and providing more objective clinical data to support colposcopic decision-making[28-30]. Additionally, artificial intelligence (AI)-driven image analysis may reduce subjective interobserver variability and improve diagnostic consistency[31,32]. Overall, addressing diagnostic challenges requires integrating training, risk-based approaches, and emerging technologies.

TZ classification and clinical significance

The TZ, defined as the area between the original and new SCJ, is the anatomic region where most cervical cancers originate[19]. Accurate classification of TZ types is critically important because the TZ directly informs the need for ECC and guides the appropriate depth and extent of excisional procedures when indicated[33]. Inaccurate assessment may lead to omission of necessary diagnostic steps, thereby increasing the risk of undetected endocervical lesions. This skill is becoming increasingly essential with an aging population and ongoing discussions about extending cervical cancer screening to older age groups, where type 3 TZs are more prevalent[34,35]. Consistent with the existing literature, the findings herein confirmed that type 2 and 3 TZs pose greater challenges to observers and are associated with lower accuracy compared to type 1 TZs[6]. However, the iDECO training programme successfully improved TZ classification accuracy, underscoring the value of structured education in enhancing reliability. Given the profound implications for treatment planning and follow-up protocols, these improvements represent a significant advancement for clinical practice.

Intelligent design as a driver for engagement and efficacy

A key strength of the iDECO platform lies in the intelligent design, which appeared to foster high user engagement and effective learning outcomes. This strength was reflected in a high posttest completion rate (90.24%) and a strong preference for iDECO over traditional methods (83.56%) among trainees. Participants particularly valued the interactive features of the platform, such as personalized feedback and gamified pathways, which offer a level of tailored guidance often lacking in conventional training settings. This enhanced engagement was associated with substantial competency gains. The 1.62-fold improvement in diagnostic accuracy is noteworthy when contextualized against the limited literature on traditional training. For example, a one-day European training programme reported only a marginal increase in diagnostic scores (from 3.37 to

3.7 out of 10)[36], while other studies have shown no significant improvement[37,38]. The principles of established learning theories may offer a framework for understanding the more pronounced effect of the iDECO. The interactive elements of the platform could support learner autonomy and competence, aligning with tenets of self-determination theory[39,40]. Simultaneously, the structured, intuitive interface is designed to reduce extraneous cognitive load, a core principle of cognitive load theory that facilitates focus on complex learning tasks[41,42]. This combination of motivational support and cognitive efficiency may contribute to high perceived usefulness and ease of use, a finding consistent with the technology acceptance model[43,44]. These observations collectively suggest that intelligent design is a pivotal element in developing effective and scalable digital medical education tools.

International implementation and adaptation

Baseline diagnostic accuracy and improvement magnitude varied considerably among different training cohorts. The two international training programmes in Mexico and Mongolia demonstrated the lowest baseline diagnostic accuracy but achieved the most substantial post-training improvements. The initially poor baseline performance may be partly attributed to the use of English-language materials instead of the native languages of the participants, potentially underestimating the true diagnostic capabilities due to language-related comprehension barriers[45]. However, the superior posttest performance indicates that the training content and local expert adaptations during Q&A sessions were highly effective. Moreover, the variation in expert instructors leading different Q&A sessions, each bringing unique expertise and teaching methodologies, likely contributed to the observed differences in trainee improvement rates. The smaller cohort sizes in international training programmes facilitated more interactive educational approaches, allowing focused attention on individual participants during Q&A sessions compared to larger Chinese programmes where individual attention was more challenging to provide. Additionally, the relative scarcity of systematic colposcopy training opportunities in Mexico and Mongolia may have contributed to the more dramatic improvements observed[5]. However, the small sample sizes and individual variation may have amplified improvement measurements, necessitating cautious interpretation of these findings. Despite these considerations, the results suggest that the platform demonstrates adaptability across diverse linguistic and clinical environments, indicating potential for broader implementation with appropriate localization strategies.

User satisfaction and the evolving role of educators

High satisfaction with iDECO-based training reflects alignment with contemporary learning expectations, offering personalized recommendations, visualized feedback, and flexible scheduling that traditional methods lack. However, the disparity in willingness to recommend between urban and rural Chinese participants reveals the impact of digital divide on educational equity because the lower satisfaction among rural users likely stems from infrastructure limitations and digital literacy gaps[46,47]. User preferences revealed a fundamental shift in medical education paradigms. The strong preference for interactive content (video courses, Q&A, and image interpretation) over static materials, coupled with 77% supporting VR integration, indicates that passive knowledge consumption is becoming obsolete[48]. The pronounced demand for expert-led Q&A sessions over peer experience sharing demonstrates that learners continue to value authoritative guidance in medical knowledge acquisition, confirming that expertise remains indispensable in the learning process. However, this preference pattern also signals a necessary evolution in expert involvement. Rather than simply delivering standardized content, experts must transition toward facilitating personalized skill development and fostering critical thinking capabilities[49,50]. This transformation acknowledges that while expert knowledge remains fundamental to medical education, the methods of knowledge transmission must adapt to meet the evolving expectations of learners for interactive, personalized learning experiences.

Limitations and future directions

Several limitations should be acknowledged in interpreting the findings of the current study. First, although the digital platform yielded significant gains in colposcopy competence, the effectiveness in clinical settings remains to be proven. To close the loop between simulation and clinical practice, future research should correlate simulation scores with provider performance, behavioral patterns, and patient outcomes in real-world environments[51]. Moreover, assessments of learning

curves, knowledge decay, and long-term skill maintenance are essential to determine the durability of training effects. Second, the current repository, primarily composed of domestic and relatively typical cases, may not adequately capture the clinical variability and standards encountered internationally. To ensure continued relevance, the platform requires regular updates that incorporate emerging evidence and expand case diversity, particularly to reflect atypical presentations and evolving disease patterns in the post-HPV vaccination era. Third, the current platform provided limited support for communication skills and other non-technical competencies essential to clinical practice. As a next step, incorporating AI-driven standardized patients and multimodal simulations could enhance interactivity and realism, fostering more comprehensive clinical readiness. Finally, structural barriers, such as the digital divide and uneven technological literacy, may hinder adoption, particularly in low-resource settings. Addressing these requires systematic assessment of access gaps and the development of sustainable implementation strategies, including localized training networks and adaptive delivery models.

Conclusions

Our multi-national evaluation of iDECO demonstrates its significant potential as an effective, scalable solution for improving colposcopy competence across diverse healthcare environments. The platform successfully enhanced diagnostic accuracy with high participant satisfaction, supporting the value of intelligent, interactive educational approaches. Despite certain limitations regarding real-world application, iDECO offers a promising pathway toward more equitable colposcopy workforce development and improved cervical cancer prevention outcomes worldwide.

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Conflict of interest statement

No potential conflicts of interest are disclosed.

Author contributions

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Data availability statement

The data generated in this study are available upon request from the corresponding author.

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