Impact of Intraoperative Ultrasound-Guided Loop Electrosurgical Excision Procedure With Individualized Marking on Perioperative Stress Responses, Immune Parameters, and Clinical Outcomes: A Comparative Study With Conventional Surgery

Ann. Ital. Chir., 2025 96, 12: 1633–1640
https://doi.org/10.62713/aic.4331

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AIM: This study compared the standard loop electrosurgical excision procedure (LEEP) with an enhanced technique incorporating intraoperative ultrasound guidance and individualized marking for high-risk human papillomavirus (HPV)-associated cervical lesions. The primary focus was on their differential impact on stress injuries incurred during the perioperative period. Furthermore, secondary outcomes included surgical precision, modulation of local immune microenvironment, and clinical endpoints, such as complications, HPV clearance, and recurrence.

METHODS: This retrospective cohort study included high-risk HPV-induced cervical intraepithelial neoplasia (CIN) II–III patients (n = 122) who were treated between January 2022 and March 2024. Patients were divided into two groups: an observation group (n = 58), which received intraoperative ultrasound-guided LEEP with individualized marking, and a control group (n = 64), which received conventional LEEP. The outcome measures evaluated were (1) perioperative stress hormones and inflammatory markers, (2) surgical parameters (intraoperative blood loss, margin positivity, and cervical canal adhesion rates), (3) postoperative complications (infection, bleeding, and cervical canal stenosis), and (4) HPV clearance and recurrence rates.

RESULTS: Postoperative stress and the levels of inflammatory markers were significantly reduced in the observation group compared to the conventional group ($p < 0.05$). However, the observation group demonstrated significant improvement, including reduced intraoperative bleeding, fewer positive margins, and increased HPV clearance rates ($p < 0.05$). Regarding postoperative complications, the observation group exhibited a significant reduction in acute infection and Cervical canal adhesion rates compared with the control group ($p < 0.05$). Finally, postoperative Visual Analogue Scale (VAS) and Hospital Anxiety and Depression Scale-anxiety (HADS-A) scores were lower in the observation group than in the control group ($p < 0.05$).

CONCLUSIONS: The use of intraoperative ultrasound-guided LEEP with individualized marking is associated with attenuated perioperative stress responses and a more preserved immune microenvironment. This, in turn, improves HPV clearance rates and diminishes postoperative complication risks.

Keywords: loop electrosurgical excision procedure; human papillomavirus; cervical intraepithelial neoplasia; stress response

Introduction

Cervical cancer (CC) is the fourth most frequently diagnosed cancer among women globally. According to World Health Organization (WHO) estimates, there were approximately 604,000 new cases and 342,000 mortalities in 2022, with over 80% occurring in developing countries [1,2]. Persistent infection with high-risk human papillomavirus (HPV) is the primary etiology of CC, detected in approximately 99.7% of cases [3]. Without appropriate treatment, cervical intraepithelial neoplasia (CIN), the known precursor of CC, can progress to an invasive condition [4]. Currently, the loop electrosurgical excision procedure (LEEP) remains the gold standard for managing high-grade CIN and early-stage CC, providing both diagnostic and therapeutic benefits [5]. Nevertheless, despite its widespread application, conventional LEEP is limited by variable accuracy, postoperative complications, and suboptimal recovery outcomes.

Precision in resection depth and margins during LEEP often relies on visual inspection and tactile guidance, which elevates the risk of positive margins, residual lesions, and recurrence [6]. Additionally, inaccurate intraoperative assessment of endocervical canal depth and transformation zone extent may result in unnecessary excision of healthy tissues, thereby elevating the likelihood of postoperative bleeding, infection, and cervical canal stenosis or adhesion [7]. These limitations can also induce perioperative stress responses, compromise immune function, impede HPV clearance, delay wound healing, and potentially contribute to higher recurrence rates [8].

Submitted: 1 September 2025 Revised: 15 October 2025 Accepted: 23 October 2025 Published: 10 December 2025
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Recent advancements include the use of intraoperative ultrasound during LEEP. By offering real-time visualization of cervical anatomical structure to guide lesion targeting, this technique is expected to improve the accuracy of overall resection [9]. While ultrasound-guided LEEP has been associated with short-term positive outcomes and reduced long-term recurrence in CIN [10,11], limited studies have examined its impact on perioperative stress injury. Additionally, the diagnostic capability of current ultrasound systems is constrained by their reliance on two-dimensional or low-fidelity three-dimensional imaging, which reduces sensitivity for subtle lesions, such as occult HPV-related CIN. Practical application of ultrasound guidance is further hampered by considerable variability in efficacy, largely attributed to the lack of standardized approaches for marking HPV-infected cervical lesions.

To address these gaps, this study proposes an optimized LEEP protocol that integrates intraoperative ultrasound guidance with individualized lesion marking. Following a multi-dimensional assessment (HPV genotyping, colposcopic mapping of lesion extent, and ultrasound imaging), visual markers are applied to the ectocervix and within the endocervical canal. Real-time ultrasound-guided resection then enables a personalized "precise localization-targeted resection" approach. We systematically compared perioperative stress responses between this surgical method and conventional LEEP. The findings offer novel evidence to personalize management of HPV-related cervical lesions and guide approaches for CC prevention and control.

Methods

Study Participants and Their Selection Criteria

This retrospective study enrolled 58 women with CIN who received ultrasound-guided intraoperative LEEP and individualized lesion marking at Shijiazhuang Maternal and Child Health Hospital between January 2022 and March 2024, and 64 baseline-matched patients who received conventional LEEP.

Inclusion criteria for patient selection were as follows: (1) women aged 25–45 years of reproductive age with pathologically confirmed CIN II–III associated with high-risk HPV infection, (2) lesion extent $\leq$2/3 of the cervical surface area (based on preoperative colposcopy), and (3) those with no immediate pregnancy plans, and consent for cervical function-preserving management. Exclusion criteria included (1) known hypersensitivity to intraoperative ultrasound contrast agents or markers, (2) colposcopy-confirmed abnormal cervical anatomical structure, (3) concurrent gynecologic malignancy or cervical metastasis, and (4) use of immunosuppressant, hormone therapy, or cervical surgery within the 3 months.

The required sample size was calculated using PASS 15.0 software (NCSS, Santa Clara, CA, USA), with at least 55 participants per group. After screening, 64 patients who underwent conventional LEEP were included in the conventional group, and 58 patients who received ultrasound-guided LEEP with individualized lesion marking were included in the observation group. This study was approved by the ethics committee of Shijiazhuang Maternal and Child Health Hospital (No: 202218), and written informed consent was obtained from all participants before their enrollment.

Surgical Protocols

Both patient cohorts received surgical procedures by the same surgical team. All patients underwent a standardized preoperative assessment, including gynecological examination, vaginal secretion analysis, and complete blood count. The extent of cervical lesion, cervical canal length, and their spatial relationships to adjacent tissues were evaluated preoperatively using transvaginal three-dimensional ultrasound. Prophylactic antibiotics (2 g cefuroxime intravenously) were administered 30 minutes before surgery.

For the conventional group, surgical procedures were conducted with a high-frequency electrosurgical unit (2001-3250150, ICC 300, ERBE, Baden, Württemberg, Germany). Under colposcopic guidance, lesion extent was defined, and the generator was adjusted to a 60–80 W resection power and 40–50 W coagulation power. The excision extended 2–3 mm beyond the outer margin of the lesion, with resection depth tailored to disease severity (15–20 mm for CIN II–III). Subsequent hemostasis was achieved using a spherical electrode. The depth of resection was determined by preoperative colposcopic evaluation, biopsy pathology estimates of lesion depth, and the clinical experience of the surgeon. The resection aims to cover the transformation zone and extend at least 3 mm beyond the deepest point of the estimated lesion while minimizing unnecessary resection of normal cervical tissue. Finally, the surgical site was dressed in sterile gauze, which was removed 24 hours postoperatively.

For the observation group, ultrasonography was performed with a GE Voluson E10 using a transvaginal three-dimensional volume probe (frequency range 5–9 MHz). Imaging depth was set to 10–12 cm, and gain was increased by +2 dB to optimize the visualization of cervical lesions. Initially, to achieve individualized marking, the entire cervix was scanned to define lesion boundaries, using a transvaginal ultrasound probe. Guided by ultrasound findings, HPV genotyping, and colposcopy assessment, 0.5% methylene blue (0.1–0.2 mL per site) was injected 2–3 mm outside the lesion margin. Injection points were spaced 5–8 mm apart to form a circumferential "marking ring". For cervical canal involvement, a thin (1 mm diameter) catheter was introduced via the external os, and methylene blue was then instilled into the proximal endocervical canal to a depth of ~20 mm to demarcate intracanalicular lesions.

Before resection, the extent of the marking was reconfirmed by ultrasound. Resection was performed 1–2 mm outside the marking ring, with the resection depth set at least 2 mm

beyond the maximum depth of the lesion to ensure a safety margin. Real-time ultrasound monitoring was used during resection; if residual lesions were found, the resection field was immediately adjusted. Following resection, the wound bed and endocervical canal were scanned to confirm the absence of residual lesions.

All patients completed a minimum of one year of follow-up, with monthly re-examinations to monitor recovery and disease status.

Outcome Measures

Various outcome measures assessed during this study were as follows:

• Surgical outcomes: The duration of surgery was recorded for all participating individuals. Intraoperative blood loss was quantified by subtracting the volume of intraoperative irrigation fluid from the aspirator collection and adding the weight gain of surgical gauze, assuming 1 gram is equivalent to 1 mL of blood. Postoperative margin status was evaluated, with positivity defined as a CIN lesion present at the surgical margin.

• Perioperative stress responses: Venous blood (3 mL) was collected from each patient at the morning before surgery (T0), the first postoperative morning (T1), and the morning after surgery (T2). All blood samples were collected between 8 AM and 9 AM to minimize the circadian effects. Serum was isolated by centrifugation, cortisol (Cor) was determined using a chemiluminescence analyzer, and epinephrine (E) and norepinephrine (NE) were measured using Enzyme-linked immunosorbent assay (ELISA).

• Inflammatory markers: Levels of inflammatory markers (interleukin [IL]-1β, IL-6, and tumor necrosis factor-α [TNF-α]) were quantified by ELISA at one hour post-surgery (acute phase) and 24 hours post-surgery (recovery phase).

• Immune parameters: During the postoperative reconstruction phase (72 hours post-operation), cluster of differentiation (CD)4^+/$CD8^+$ T and natural killer (NK) cell proportions were measured by flow cytometry using anti-CD3-PerCP (Batch number: 333185), anti-CD4-FITC (Batch number: 333142), anti-CD8-PE (Batch number: 333107), and anti-CD56-APC (Batch number: 331152) antibodies (BD Biosciences, Franklin Lakes, NJ, USA). NK cells were defined as CD3-$CD56^+$ lymphocytes. An isotype control antibody was used to set the negative threshold. Gating proceeded by delineating lymphocyte population on the FSC/SSC scatter plot, followed by quantifying $CD4^+$ and $CD8^+$ T cell subsets within $CD3^+$ cells and $CD56^+$ NK cells within CD3-cells.

• Adverse reactions: The incidence of postoperative acute infection (fever >38.5 °C or purulent discharge with leukocytosis), postoperative bleeding requiring secondary hemostasis, cervical canal stenosis (decreased canal diameter or patency), and cervical canal adhesion (near-complete loss of patency or requiring intervention) were recorded. These complications were identified at the three-month gynecological assessment.

• Prognosis: HPV DNA testing was conducted at 3, 6, and 12 months to determine viral clearance. Colposcopy and cervical biopsy were performed at the 12-month time point to assess recurrence of CIN II–III.

• Subjective perceptions: Postoperative pain was assessed using a 10-point Visual Analogue Scale (VAS) [12], where 0 indicates no pain and 10 indicates the worst imaginable pain. Anxiety and depression were screened using the Hospital Anxiety and Depression Scale (HADS) [13], comprising 14 items (7 for anxiety and 7 for depression). A subscale score of $\geq$8 is considered potentially indicative of anxiety or depression.

Statistical Analysis

Statistical analyses were performed using SPSS 30.0 (SPSS Inc., Armonk, NY, USA). Categorical data were expressed as n (%) and analyzed using the chi-square test. For continuous variables, normality of the distribution was evaluated using the Shapiro-Wilk test. Normally distributed variables were presented as mean $\pm$ standard deviation ($\bar{x} \pm$ s). Furthermore, between-group differences were analyzed using the independent samples *t*-test, within-group comparisons using the paired *t*-test, and multiple-group comparisons using repeated-measures analysis of variance followed by Bonferroni post-hoc testing. Statistical significance was set to a *p*-value of less than 0.05.

Results

Comparison of Clinical and Baseline Data Between the Two Groups

The inter-group comparisons of baseline characteristics, such as age, disease duration, pathological staging, body mass index (BMI), CIN type, and reproductive history, revealed no statistically significant differences ($p > 0.05$), confirming clinical comparability between the two groups (Table 1).

Comparison of Surgical Outcomes Between the Two Groups

Surgical duration was found to be comparable between the conventional and observation groups ($p > 0.05$). However, the observation group showed less intraoperative bleeding and lower margin positivity than the conventional group ($p < 0.05$, Table 2).

Comparison of Perioperative Stress Responses, Immune Parameters, and Clinical Outcomes

No significant intergroup differences were observed in baseline levels (T0) of Cor, E, or NE ($p > 0.05$). At the T1 time point, all three indicators increased significantly from baseline in both groups, with a smaller increase in the observation group than in the conventional group ($p < 0.05$). At the T2 time point, their values declined substantially than at

Table 1. Comparison of baseline characteristics between the conventional and observation groups.

Groups	n	Age (years)	Duration of disease (months)	Pathological staging (II/III)	BMI (kg/m^2)	Reproductive history (Yes/No)	CIN II/CIN III
Conventional group	64	34.31 ± 5.64	6.14 ± 2.95	34 (53.13)/30 (46.88)	23.00 ± 2.94	52 (81.25)/12 (18.75)	7 (10.94)/57 (89.06)
Observation group	58	34.33 ± 5.73	5.95 ± 2.20	29 (50.00)/29 (50.00)	23.67 ± 2.29	52 (89.66)/6 (10.34)	6 (10.34)/52 (89.66)
Statistical		t = 0.015	t = 0.405	χ^2 = 0.119	t = 1.406	χ^2 = 1.709	χ^2 = 0.011
p-value		0.988	0.686	0.730	0.162	0.191	0.916

Note: BMI, body mass index; CIN, cervical intraepithelial neoplasia.

Table 2. Comparison of surgical conditions between the two groups.

Groups	n	Surgical duration (minutes)	Intraoperative bleeding (mL)	Margin positivity [n (%)]
Conventional group	64	12.23 ± 1.94	25.77 ± 8.77	16 (25.00)
Observation group	58	12.05 ± 1.53	21.24 ± 5.63	6 (10.34)
Statistical		t = 0.574	t = 3.352	χ^2 = 4.421
p-value		0.567	0.001	0.036

T1 in both groups ($p < 0.05$). Cor and E values remained higher at T2 than baseline (T0) in conventional group ($p < 0.05$). Furthermore, both groups showed no significant difference in NE at T2 ($p > 0.05$). However, Cor and E were lower in the observation group than in the conventional group ($p < 0.05$).

Repeated measures analysis of variance (ANOVA) revealed a significant group-by-time interaction effect for Cor, E, and NE ($p < 0.05$), indicating a more rapid reduction in stress response in the observation group than in the control group. Inflammatory markers, IL-6, TNF-α, and IL-1β concentrations were substantially reduced in the observation group across both the acute and recovery phases than the conventional group ($p < 0.05$).

Within-group comparison revealed reduced levels of inflammatory markers during the recovery phase compared to the acute phase in both cohorts ($p < 0.05$). In the postoperative reconstruction phase, immunophenotyping demonstrated higher proportions of CD4$^+$/CD8$^+$ T lymphocytes and NK cells in the observation group ($p < 0.05$, Fig. 1).

Comparison of Postoperative Complications Between the Two Groups

In terms of safety, postoperative bleeding rates were comparable between the cohorts ($p > 0.05$). Conversely, patients in the observation group exhibited a significantly lower incidence of acute infection ($p = 0.038$) and fewer cases of cervical canal adhesion relative to the conventional group ($p = 0.038$, Table 3).

Comparison of HPV Clearance and Recurrence Rates Between the Two Groups

Follow-up of these patients revealed higher HPV clearance rates at 3 and 6 months in the observation group than in the conventional group ($p < 0.05$). However, the 1-year recurrence rates did not differ significantly between the two groups ($p > 0.05$, Table 4).

Comparison of Patient-Reported Subjective Outcomes Between the Two Groups

Regarding subjective outcomes, VAS pain scores on postoperative day one were lower in the observation group compared to the conventional group ($p < 0.05$). At one month post-operation, Hospital Anxiety and Depression Scale-anxiety (HADS-A) and Hospital Anxiety and Depression Scale-depression (HADS-D) scores were within the normal range in both groups ($\leq$7), indicating no significant anxiety or depression. However, the HADS-A score was significantly lower in the observation group than the control group ($p < 0.05$), suggesting a lower degree of anxiety after surgery (Table 5).

Discussion

This study reveals clear advantages of ultrasound-guided LEEP with individualized marking over the conventional approach. This optimized strategy showed higher surgical precision, evidenced by lower intraoperative bleeding and reduced positive-margin rates, and was associated with attenuated perioperative stress responses, fewer postoperative complications, and greater short-term HPV clearance. Although the one-year recurrence rate did not differ significantly between the two groups, patients in the optimized group exhibited less postoperative pain and anxiety. Overall, this approach improves procedural accuracy and delivers multi-dimensional clinical benefits by reducing stress, protecting immune function, and enhancing patient-reported subjective outcomes.

Intraoperative ultrasound offers real-time 3 dimensions (3D) delineation of lesions, wherein lesions appear as hypoechoic regions distinct from surrounding cervical tissue. When integrated with individualized methylene blue marking of the lesion periphery and any endocervical canal involvement, this approach enabled the observation group to achieve highly accurate resection margins [14]. This improved precision mitigates unnecessary resection of normal

Table 3. Comparison of postoperative complications between the conventional and observation groups.

Groups	n	Postoperative bleeding [n (%)]	Acute infection [n (%)]	Cervical canal stenosis [n (%)]	Cervical canal adhesion [n (%)]
Conventional group	64	7 (10.94)	11 (17.19)	5 (7.81)	11 (17.19)
Observation group	58	3 (5.17)	3 (5.17)	1 (1.72)	3 (5.17)
χ^2		1.344	4.324	2.412	4.324
p-value		0.246	0.038	0.120	0.038

Table 4. Comparison of prognosis between the conventional and observation groups.

Groups	n	HPV clearance rate		Recurrence rate
		3 months after surgery	6 months after surgery	
Conventional group	64	35 (54.69)	47 (73.44)	7 (10.94)
Observation group	58	45 (77.59)	53 (91.38)	2 (3.45)
χ^2		7.067	6.626	-
p-value		0.008	0.010	0.168

HPV, human papillomavirus. "-" indicates that the statistic was not calculated because the assumption of the chi-square test was violated (more than 20% of the cells had an expected cell count < 5), therefore, Fisher's exact test was used.

Table 5. Comparison of patient-reported subjective outcomes between the two groups.

Groups	n	VAS	HADS	
			HADS-A	HADS-D
Conventional group	64	3.98 ± 1.78	4.97 ± 1.78	4.28 ± 1.62
Observation group	58	2.86 ± 1.02	4.28 ± 1.35	4.22 ± 1.57
t		4.223	2.403	0.198
p-value		<0.001	0.018	0.844

Note: VAS, Visual Analogue Scale; HADS, Hospital Anxiety and Depression Scale; HADS-A, Hospital Anxiety and Depression Scale-anxiety; HADS-D, Hospital Anxiety and Depression Scale-depression.

cervical tissue and reduces neuroendocrine stimulation associated with surgical trauma. By replacing blind resection with ultrasound-guided individualized marking, collateral tissue damage was significantly reduced in the observation group.

Additionally, decreased adjustments to intraoperative electrocautery paths may indirectly attenuate the local inflammatory response. The lower postoperative stress and inflammatory markers observed in the observation group versus the conventional group are consistent with previous evidence that higher surgical precision triggers a milder stress response [15]. Furthermore, at the immune cell level, the observation group showed higher proportions of $CD4^+/CD8^+$ T and NK cells during the immune reconstruction phase than the conventional group. A potential mechanism is the decline in stress hormones, which reduces their inhibitory effects on immune cells [16], thereby enhancing HPV clearance.

Furthermore, this study observed lower rates of positive margins and cervical canal adhesions in the observation group, likely due to real-time ultrasound monitoring of endocervical depth and the transformation zone scope. Conversely, the conventional LEEP procedure relies on a two-dimensional colposcopic view, which elevates the risk of missing hidden lesions, particularly deeper infiltrative disease associated with HPV16/18 infections. This limitation can lead to either insufficient or excessive resection [17].

In this study, combining ultrasound guidance with methylene blue marking improved the accuracy of endocervical canal marking and effectively reduced cervical canal adhesions in the observation group, consistent with previous findings by Van Trappen P [18]. Moreover, precise resection minimized intraoperative thermal injury to the cervical stroma, thereby lowering the likelihood of postoperative bleeding and infection. Although the incidence of postoperative bleeding was comparable between groups, the reduced intraoperative bleeding in the observation group likely indicates more accurate hemostasis achieved under real-time ultrasound guidance.

Additionally, no significant difference in the incidence of cervical canal stenosis was observed between the two groups. This may be attributed to two factors: first, strict adherence to both approaches to avoid excessive resection of cervical canal tissue, and standard cervical wound management with routine follow-up, which may prevent severe stenosis. Nonetheless, precise ultrasound guidance should theoretically be more effective in preserving the structural integrity of the cervical canal, and future studies with larger sample sizes may reveal potential differences. Moreover, the higher HPV clearance in the observation group is potentially driven by two mechanisms. First, a lower positive margin rate eliminates residual disease that acts as a reservoir for persistent infection. Second, precise resection reduces damage to normal cervical tissue, helping maintain the local immune microenvironment and enhancing antiviral immune surveillance.

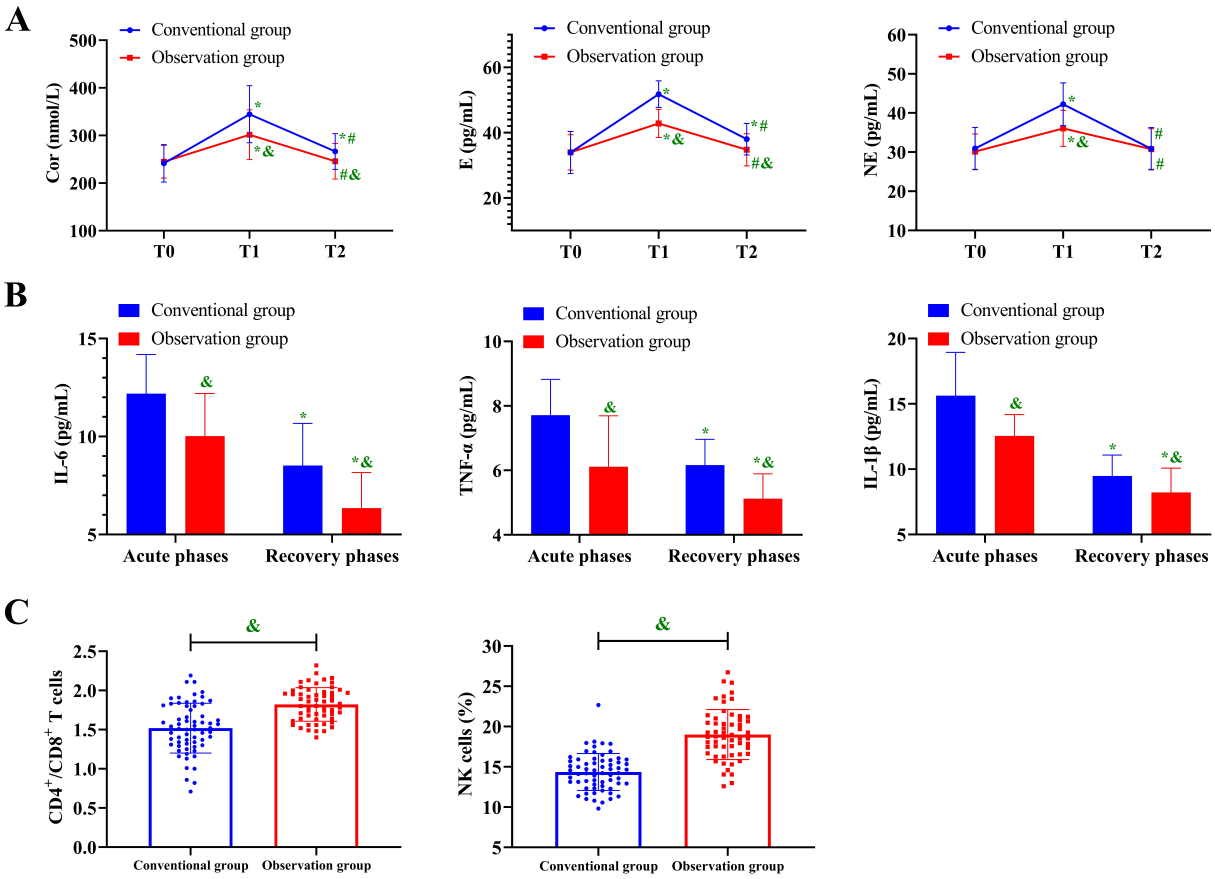

Fig. 1. Comparison of perioperative stress indicators between the conventional and observation groups. (A) Comparison of serum stress indicators, including Cor, E, and NE. * represents the comparison with T0 within the group ($p < 0.05$), # represents the comparison with T1 within the group ($p < 0.05$), & represents the comparison with the conventional group at the same time ($p < 0.05$). (B) Comparison of serum inflammatory factors, including IL-6, TNF-α, and IL-1β. * represents the comparison with the acute phase within the group ($p < 0.05$), & represents the comparison with the conventional group at the same time ($p < 0.05$). (C) Comparison of immune cells, such as $CD4^+/CD8^+$ T lymphocytes and NK cells. & indicates a comparison between the two groups ($p < 0.05$). Note: Cor, cortisol; E, epinephrine; NE, norepinephrine; IL, interleukin; TNF-α, tumor necrosis factor-α; CD, cluster of differentiation; NK, natural killer.

The absence of significant variation in the 1-year recurrence rate likely indicates the limited follow-up period and the small sample size (n = 122). Meanwhile, spontaneous HPV clearance is influenced by multiple hosts and viral factors, introducing variability that may further obscure intergroup effects. Regarding subjective outcomes, the observation group showed lower VAS and HADS-A scores, further re-emphasizing that ultrasound-guided LEEP with individualized marking can reduce postoperative pain. The lower anxiety in the observation group, with HADS-D remaining within the normal range in both cohorts, further suggests that greater surgical precision may reduce anticipative anxiety associated with fear of recurrence.

This study assesses optimized surgical management of HPV-associated cervical lesions. The findings support adopting an "ultrasound guidance plus individualized marking" technique in tertiary hospitals with intraoperative ultrasound capability. Integrating perioperative stress management within the enhanced recovery after surgery (ERAS) protocol is also crucial; by reducing surgical trauma under ultrasound guidance, recovery of both physical and psychological well-being can be accelerated.

The principal limitations are the small sample size and short follow-up time. Long-term outcomes, including postoperative recurrence and persistent HPV infection, need further validation in larger cohorts with extended follow-up. Furthermore, as the prognostic impact of HPV subtypes was not assessed, subtype-specific effects may be masked (e.g., differences between high-risk and low-risk HPV infections). Although methylene blue labeling is helpful for intraoperative localization, its potential for tissue diffusion may affect labeling boundaries and reduce marking precision, representing a methodological limitation. Additionally, patients were enrolled from 2022 to 2024; sub-

tle changes in clinical practice or procedural details during this period could have introduced potential temporal bias despite a single surgical team. Despite standardizing blood sampling (8:00–9:00 AM), differences in physiological and psychological states across time points (e.g., preoperative anxiety, postoperative pain, and drug effects) could confound measurements of stress hormones and inflammatory factors. Finally, the reliance of the individualized marking protocol on the operator's experience highlights the need for more standardized operating procedures.

Conclusions

In patients with HPV-associated cervical lesions, LEEP conducted under intraoperative ultrasound guidance with individualized marking yields significant advantages. It significantly lowers the risk of short-term complications and enhances HPV clearance, likely through improved surgical precision, reduction of perioperative stress responses, and preservation of the local immune microenvironment. Future research should include larger sample cohorts and extended follow-up to further explore the association between ultrasound parameters and HPV clearance. These measures are critical for standardizing the clinical application of this surgical technique.

Availability of Data and Materials

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

Author Contributions

YQB conceived and designed the research study, acquired and analyzed the data, and wrote the initial draft of the manuscript. SW provided technical support for the acquisition and analysis of the data, performed statistical analysis, and contributed to the interpretation of the data. LZ provided expertise in the field of study, contributed to the interpretation of the data. SW and LZ contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

All patients provided informed consent to participate in this study, and the study was designed in adherence to the principles of the Declaration of Helsinki. This study was approved by the ethics committee of Shijiazhuang Maternal and Child Health Hospital (No: 202218).

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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