

Current Trends and Future Directions in the Prevention, Screening and Management of Cervical Cancer - A Review

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DOI: <https://doi.org/10.52403/ijrr.20260111>

ABSTRACT

Cervical cancer ranks as the second most common cancer affecting women globally, contributing to 20% of the total cancer burden. In 2023, Cancer.Net® reported around 13,960 new cases and 4,310 deaths among women due to this disease. By 2026, projections suggest that less developed countries will see a rise of 528,000 new cervical cancer cases, with 85% occurring in emerging nations. The disease is responsible for approximately 266,000 deaths annually, making up 8% of all cancer-related fatalities. In the U.S., about 11,500 women are diagnosed with cervical cancer each year, and roughly 4,000 dies from it. Despite these figures, developing nations have made strides in reducing cervical cancer rates through screening initiatives. Although prevention efforts-driven by nonprofits and government programs-have been in place for years, their impact has been modest. Initially focused on detecting and treating precancerous conditions, recent advancements now include HPV

vaccination. In India, an estimated 272.8 million women qualify for cervical cancer screening, and 59.7 million girls are eligible for HPV immunization. Risk factors for cervical cancer include infection with HPV, smoking, having multiple sexual partners, long-term use of oral contraceptives, and early sexual activity. The future of management is being shaped by innovations such as immunotherapies, robotic surgery, self-sampling methods, and diagnostics aided by artificial intelligence. In order to meet the WHO 2030 eradication targets, this assessment addresses research gaps in the areas of epidemiology, prevention, screening, diagnosis, treatment, and future directions.

Keywords: cervical cancer, current trends, HPV vaccination, screening, diagnostics, management and cervical cancer prevention.

INTRODUCTION

Cervical cancer is characterized by the abnormal growth of cells in the cervix. It still

contributes significantly to cancer-related morbidity and mortality, particularly in low- and middle-income nations, despite tremendous advances in medical research. Persistent infection with high-risk human papillomavirus (HPV) strains, which are closely linked to cellular transformation and cervical epithelial carcinogenesis, is the main cause of the disease.

The management of cervical cancer has changed over the last few decades due to creative preventative and early detection techniques. The prevalence of high-risk HPV infections has dramatically decreased as a result of the widespread implementation of HPV vaccination programs, especially among younger people. At the same time, developments in screening technologies, like HPV DNA testing and liquid-based cytology, have improved early detection capabilities, leading to better treatment results. As the fourth most frequent disease in women, cervical cancer poses a serious threat to global health. Over 600,000 new cases and 340,000 fatalities are estimated to occur each year, with the majority occurring in underdeveloped nations, according to the World Health Organization (WHO). Nearly 99% of all cervical infections are caused by persistent infection with high-risk human papillomavirus (HPV), especially strains 16 and 18.

Early detection rates have been greatly increased by developments in screening methods, such as the use of liquid-based cytology and HPV DNA testing. Compared to conventional Pap smear tests, these techniques have shown improved sensitivity and specificity, especially when paired with risk-based algorithms. Additionally, new screening techniques are being developed, such as self-sampling kits, which have the potential to reach underprivileged groups.

Treatment is still difficult for those that are discovered later. Despite having higher survival rates, conventional treatments including radiation, chemotherapy, and surgery are frequently linked to serious adverse effects and have limited effectiveness in cases of severe or recurrent cancer. More efficient and customized care is being made possible by recent developments in immunotherapy, targeted medicines, and the use of artificial intelligence in diagnosis and treatment planning.¹

Reviewing recent developments and current trends in cervical cancer research and treatment is the goal of this presentation. By filling in the gaps in prevention, diagnosis, and treatment, it offers insights into how public health initiatives and new technologies might work together to eliminate cervical cancer worldwide.

EPIDEMIOLOGY AND GLOBAL BURDEN

Cervical cancer remains a significant public health concern worldwide, particularly in low- and middle-income countries (LMICs). Over the past two decades, it has consistently ranked among the most common malignancies affecting women. In India, the highest incidence is observed among women aged 55 to 59 years. Although the average annual risk of cervical cancer among women aged 30 to 64 has declined by 1.8%, this age group still accounts for approximately 16% of all female cancer cases. The high prevalence of human papillomavirus (HPV)-exceeding 10% in women over 30-and limited access to screening contribute to the disease's persistence in South and Southeast Asia (Kunkule R. et al., 2020).²

Globally, cervical cancer ranks fourth among cancers diagnosed in women, with an estimated 662,044 new cases and 348,709

deaths in 2022 (ASIR: 14.12/100,000; ASMR: 7.08/100,000). China and India bear a disproportionate share of the burden, accounting for 23% and 19% of cases, and 16% and 23% of deaths, respectively (J Wu et al., 2025).³

The World Health Organization (WHO) has proposed a global strategy to eliminate cervical cancer, aiming to reduce incidence rates to fewer than four per 100,000 women annually. Achieving this target could prevent an estimated 350,000 deaths worldwide, including 44,750 in China. The burden of cervical cancer is unevenly distributed across regions. In Europe, approximately 58,000 new cases (10.7 per 100,000 women) and 26,000 deaths (3.76 per 100,000 women) are reported annually. In the United States, the adjusted incidence rate between 2000 and 2018 was 11.5 per 100,000 person-years among women aged 15–75 years. Australia recorded 942 new cases and 222 deaths in 2022, corresponding to an incidence rate of 7.1 per 100,000 women. However, LMICs account for nearly 80% of global cervical cancer cases, largely due to limited screening programs and the high cost of HPV vaccination. Between 2005 and 2020, cervical cancer rose from the seventh to the sixth leading cause of cancer-related deaths among adult women and became the third most common cause among women aged 20–39 years, with an average annual increase of 2.72% in mortality across all age groups (Xu M. et al., 2024).⁴

Persistent infection with high-risk HPV strains is the primary etiological factor in cervical carcinogenesis. HPV types 16 and 18 are responsible for over 75% of cervical cancer cases, with HPV-16 alone accounting for more than 50% and HPV-18 for approximately 10% (Al-Rawi A.M. et al.,

2024)⁵. Other oncogenic HPV types also contribute to malignancy. In contrast, low-risk HPV strains such as types 6 and 11 are typically associated with benign conditions like condylomata acuminata (anogenital warts). Although over half a million HPV infections are diagnosed annually, most are low-grade and resolve spontaneously within two years (Fowler et al., 2023).⁶

ETIOLOGY & ROLE OF HPV IN CARCINOGENESIS

1. HPV as a Central Etiological Agent

The pivotal role of human papillomavirus (HPV) in cervical cancer was firmly established by Zur Hausen (2009), whose groundbreaking research identified high-risk HPV types—particularly HPV-16 and HPV-18—as causative agents in approximately 70% of cervical cancer cases. This discovery catalyzed the development of prophylactic vaccines and molecular diagnostic tools, revolutionizing cervical cancer prevention and early detection strategies.¹

HPV is the most prevalent viral infection of the reproductive tract, with most sexually active individuals acquiring it at some point in their lives (Srivastava et al., 2018). Transmission occurs primarily through genital contact, including skin-to-skin interaction, and does not necessarily require penetrative intercourse. While most infections are transient, a subset of oncogenic HPV types can persist and lead to malignant transformation of cervical epithelial cells.⁷

2. Behavioral and Lifestyle Risk Factors

Torre et al. (2015) and Pujari et al. (2024) highlight several behavioral and environmental factors that increase

susceptibility to persistent HPV infection and subsequent carcinogenesis. These include:

- Early initiation of sexual activity and multiple sexual partners.
- Smoking, which impairs immune surveillance and promotes oncogenic mutations.
- Immunosuppression, either due to medical conditions or immunosuppressive therapy.
- Poor genital hygiene and lack of awareness regarding HPV transmission.¹

Al-Rawi A.M. et al. (2024) further emphasize that cervical cancer is not genetically inherited, and dietary interventions alone do not prevent its onset. However, younger age at first sexual intercourse especially near menarche is associated with increased vulnerability to HPV infection and cervical neoplasia.⁵

3. Additional Contributing Factors

Okonkwo (2018) and Kunkule (2020) expand the list of contributing factors to include:

- **Chlamydia infection**, which may be asymptomatic but can act synergistically with HPV.
- **Dietary deficiencies**, particularly low intake of fruits and vegetables.
- **Use of oral contraceptives and intrauterine devices (IUDs)**, which may alter cervical epithelial integrity.
- **Exposure to diethylstilbestrol (DES) in utero**, linked to increased risk of adenocarcinoma.
- **Multiple full-term pregnancies**, which may weaken immune defenses and induce hormonal changes.

- **Family history**, though not directly genetic, may reflect shared environmental or behavioral risks.^{8,2}

4. Epidemiological Insights and Screening Importance

- Cervical cancer typically manifests in women in their mid-30s to late 40s, with age-related immune decline contributing to disease progression. Regular cervical screening remains a cornerstone of secondary prevention, enabling early detection of precancerous lesions before invasive cancer develops.
- HPV also contributes to malignancies beyond the cervix, including cancers of the anus, vulva, vagina, penis, and oropharynx, underscoring the importance of comprehensive HPV vaccination programs and public health education.⁸

CURRENT PREVENTION STRATEGIES: HPV VACCINATION

Vaccine Development and Composition

The development of HPV vaccines has significantly advanced primary prevention efforts against cervical cancer. According to Al-Rawi et al. (2024), the 9-valent HPV vaccine (Gardasil 9), approved by the US Food and Drug Administration in December 2014, offers protection against nine HPV strains: 6, 11, 16, 18, 31, 33, 45, 52, and 58. Earlier vaccines include the quadrivalent Gardasil, introduced by Merck in 2006, targeting HPV types 6, 11, 16, and 18, and the bivalent Cervarix, licensed in 2009 by GlaxoSmithKline, which focuses on types 16 and 18 (Sekar P. et al., 2024).^{5,9}

These vaccines are composed of virus-like particles (VLPs) and are administered

intramuscularly into the deltoid muscle. As noted by Manuel V et al. (2017), they are not recommended for children under nine years due to insufficient safety and immunogenicity data.¹⁰

Vaccination Guidelines and Dosing

Vaccination is recommended to begin at ages 11 or 12, though it may be initiated as early as age 9. According to Perkins RB et al. (2023), children vaccinated before their 15th birthday should receive two doses spaced 6 to 12 months apart. Individuals aged 15 or older, those who are immunocompromised, or those who receive doses less than five months apart should complete a three-dose schedule. Catch-up vaccination is advised through age 26 for those who were not vaccinated earlier.¹¹

Efficacy and Global Implementation

HPV vaccines have demonstrated high efficacy in both clinical trials and real-world settings. Harper et al. (2006) confirmed near 100% protection against persistent cervical infections and dysplasia caused by HPV types 16 and 18. Subsequent studies, such as those by Drolet et al. (2019), have shown significant reductions in HPV prevalence and cervical abnormalities in regions with high vaccination coverage.

Despite these successes, global implementation remains uneven. Goldstein et al. (2024) reported that by 2022, 125 countries had introduced HPV vaccines into their national immunization programs. However, only one-third of the global population of girls were included in these protocols, and in less developed regions, just 2.7% of women completed the full vaccine series.¹²

Primary Prevention Measures

Beyond vaccination, primary prevention includes education on safe sexual practices and early immunization. Sekar P et al. (2024) emphasized that both Gardasil and Cervarix have demonstrated short-term safety, strong immunogenicity, and effectiveness in preventing HPV infections and associated precancerous lesions. Empirical evidence also suggests that these vaccines may offer cross-protection against closely related HPV genotypes.⁹

Secondary Prevention

Secondary prevention focuses on detecting precancerous changes before they progress to cancer, typically through screening individuals without symptoms or conducting confirmatory tests in those who show symptoms or test positive during initial screening. A variety of techniques are available for cervical cancer screening. Observational research indicates that regular screening programs significantly lower the rates of invasive cervical cancer and related mortality. Common screening methods for identifying early-stage cervical abnormalities include:

1. Cervical cytology (both liquid-based and traditional methods)
2. Direct visual examination
3. Visual inspection using acetic acid
4. Visual inspection with Lugol's iodine
5. HPV DNA testing
6. Speculoscopy
7. Polar probe assessment

Additional screening approaches may be utilized depending on the specific context or project requirements.⁹

Challenges in the Indian Context

HPV vaccination holds promise for reducing cervical cancer incidence in India. Sarkar et al. (2019) found that vaccines provided protection against HPV types 16 and 18 and some cross-protection against related strains. However, their effectiveness is limited in women already infected with oncogenic HPV genotypes.⁹

Chatterjee et al., as cited by Srivastava AN et al. (2019), analyzed the status of HPV vaccination in India and identified several barriers to implementation. These include inadequate epidemiological data for disease prioritization, uncertainty regarding vaccine duration, and low public acceptance. Despite efforts to integrate HPV vaccination into the National Immunization Programme and reduce costs, these challenges continue to hinder widespread adoption.⁷

SCREENING TECHNIQUES: EVOLUTION, INNOVATION AND EFFECTIVENESS

Traditional Cytology and the Pap Smear

The Pap test also known as the Pap smear or cervical smear has long served as a primary tool for detecting precancerous and cancerous cervical changes. It involves the gentle collection of cervical cells using a swab or brush during a speculum examination, followed by microscopic evaluation. While effective, the Pap smear is not entirely reliable and may yield false-negative results, necessitating further diagnostic follow-up in cases of abnormal findings (Okonkwo DI et al., 2018).⁸

Shifting Guidelines and Screening Strategies

Screening recommendations have changed over time to reflect advances in technology and understanding of cervical cancer risk. For average-risk women, the approach has shifted from cytology alone to co-testing (cytology plus HPV testing) introduced in 2012, and more recently to primary HPV testing as the preferred method (Qin J et al., 2021)¹³. The American Cancer Society now recommends HPV testing alone every five years for individuals aged 25 to 65, citing a better balance of benefits and harms compared to cytology (Perkins RB et al., 2023).¹¹

For women aged 21 to 29, cytology alone every three years remains the standard. For those aged 30 to 65, co-testing every five years is preferred, although HPV testing alone is gaining traction as a future standard due to its simplicity and effectiveness (Bendel SL et al., 2020).¹⁴

Enhancing Access through Self-Sampling

Self-collected specimens for HPV testing have emerged as a promising strategy to expand screening access, particularly in low-resource settings. Self-swabbing allows individuals to collect cervical samples with minimal instruction, reducing the need for pelvic examinations by trained providers. This approach is under investigation for its feasibility in detecting HPV DNA methylation on specific genes, with initiatives like the NCI's Last Mile Initiative supporting regulatory exploration (Rimel BJ et al., 2022).¹⁵

Precision Diagnostics and Molecular Technologies

Advancements in molecular screening have significantly improved diagnostic sensitivity

and specificity. HPV nucleic acid testing—whether DNA or mRNA-based—offers superior accuracy compared to cytology, with sensitivity for detecting cervical intraepithelial neoplasia (CIN) exceeding 90% versus 50–70% for cytological tests. Co-testing enhances sensitivity for CIN2+ and CIN3+ lesions but may reduce specificity, leading to increased colposcopy referrals.

DNA methylation assays, including the WID-qCIN test, have demonstrated strong predictive performance when combined with HPV16/18 genotyping and cytological classification. These tests detect epigenetic changes in cervicovaginal cells caused by HPV, offering valuable triage tools for early detection.

HPV integration detection, based on understanding the mechanism of viral integration in cervical carcinogenesis, has entered clinical practice. Ongoing trials aim to compare its effectiveness with current screening methods and assess its role in predicting disease progression.

Liquid biopsies (LB) offer a noninvasive alternative to traditional tissue biopsies. Circulating tumor DNA (ctDNA) can assist in early detection, monitor treatment response, and track resistance mechanisms, enhancing clinical decision-making (Xu M et al., 2024).⁴

Artificial Intelligence in Cervical Cancer Screening

AI has become a transformative force in cervical cancer diagnostics. Automated Pap smear analysis and AI-assisted colposcopy systems have improved diagnostic precision, reduced human error, and increased

consistency. Deep learning algorithms trained on large datasets of cytological images can accurately distinguish between normal and abnormal cells, with reported accuracies ranging from 70% to 100% (Paiboonborirak C. et al., 2025; Goldstein A. et al., 2024).^{12, 16}

AI also shows promise in detecting HPV types and molecular markers, which are crucial for lesion classification and management. While AI cannot yet replace manual cytological review, it significantly enhances efficiency and supports clinical workflows (Goldstein A. et al., 2024).¹²

DIAGNOSTIC TOOLS AND STAGING IN CERVICAL CANCER

Colposcopic Examination

Colposcopy remains a fundamental diagnostic procedure for patients presenting with abnormal cervical screening results. As described by Perkins et al. (2023), the technique involves magnified visualization of the cervix following the application of 3–5% acetic acid, which highlights acetowhite plaques—indicative of high-grade precancerous lesions. These lesions often represent transformed squamous cells that spread laterally and may evolve into cervical cancer if left untreated.¹¹

Bendel et al. (2020) further emphasize the role of digital colposcopy, which has enhanced diagnostic sensitivity and accessibility. When integrated with artificial intelligence (AI), digital colposcopy allows for improved interpretation and can be particularly valuable in settings where access to trained specialists is limited.¹⁴

Kakotkin et al. (2023) highlight the growing utility of AI-guided colposcopy in primary care environments. This approach not only facilitates early detection but also supports cross-modal integration of diagnostic data from colposcopy, cytology, and HPV testing, thereby improving overall diagnostic accuracy.¹⁷

AI in Diagnostic Imaging

Radiomics has emerged as a transformative tool in gynecologic oncology, offering quantitative analysis of medical images to refine diagnosis, prognosis, and treatment planning. According to Paiboonborirak et al. (2025), radiomic features derived from MRI and ultrasound can accurately predict lymph node metastasis and VEGF expression in cervical cancer. When combined with clinical data, radiomics enhances predictions of lymphovascular space involvement and survival outcomes, contributing to a more comprehensive tumor profile.¹⁶

AI-integrated radiogenomics further strengthens predictive modeling for chemotherapy response and overall survival, offering clinicians valuable support in personalized treatment strategies.

Mustafa et al. (2023) introduced a novel multi-saliency object detection model-the Shot MultiBox detector-for cervical cancer diagnosis using ultrasound imaging. This model incorporates a deconvolution module within a residual attention framework, significantly improving detection accuracy for small-scale lesions. Additional AI-driven methods, such as automated feature extraction and contrast-based cervigram analysis using acetic acid and Lugol's iodine, have demonstrated promising results, achieving sensitivity, specificity, and

accuracy rates of 81.3%, 78.6%, and 80.0%, respectively.¹⁸

Molecular and Cytologic Testing

HPV DNA testing and liquid-based cytology remain essential components of cervical cancer screening. As noted by Pujari et al. (2024), these methods are continually evaluated for sensitivity, specificity, and feasibility across diverse populations. The integration of AI-driven diagnostic tools further enhances their performance and applicability in clinical settings.¹

Imaging for Advanced Disease

For patients with suspected advanced cervical cancer, a range of imaging modalities is employed to assess metastatic spread. Okonkwo et al. (2018) list nuclear medicine imaging, full-body CT and MRI, PET scans, intravenous urography (IVU), and chest radiography as standard techniques for evaluating disease dissemination.⁸

Kaur et al. (2012) advocate for MR imaging as the most effective modality for preoperative staging due to its superior soft-tissue resolution. MR imaging has also proven cost-effective, often replacing multiple invasive procedures such as barium enema, excretory urography, cystoscopy, and sigmoidoscopy. While CT imaging is less reliable for detecting local disease-owing to the isodensity of many tumors relative to cervical stroma-it remains valuable for assessing lymphadenopathy, monitoring distant metastases, guiding percutaneous biopsies, and planning radiation therapy.¹⁹

Cervical Cancer Staging

Staging is the most critical prognostic factor in cervical cancer, followed by nodal involvement, tumor volume, depth of stromal invasion, and lymphovascular space invasion. Al-Rawi et al. (2024) explain that the International Federation of Gynecology and Obstetrics (FIGO) staging system is widely used and includes stages 0 through IV.

Stage 0, also known as carcinoma in situ, is characterized by abnormal cells confined to the inner lining of the cervix. Stage I indicates cancer limited to the cervix. Stage II involves spread beyond the cervix without reaching the pelvic wall or lower third of the vagina. Stage III denotes extension to the lower third of the vagina, pelvic wall, or associated kidney injury. Stage IV represents the most advanced stage, with cancer spreading to the bladder, rectum, or distant organs.⁵

TREATMENT MODALITIES

Surgical Interventions in Cervical Cancer Management

Surgery remains a cornerstone in the treatment of cervical cancer, especially in its early stages. Depending on the extent of the disease, a range of surgical approaches can be adopted. For localized cervical cancer, a simple hysterectomy- involving the removal of the uterus and cervix - may suffice. In cases of more extensive local spread, a radical hysterectomy is often required. This procedure involves the removal of the uterus, cervix, parametrial tissue, upper vagina, and sometimes the fallopian tubes and ovaries, leading to infertility and premature menopause. Additionally, pelvic lymph nodes are frequently excised during these procedures to determine cancer spread and

guide further treatment (Kunkule et al., 2020; Okonkwo, 2018).^{2,8}

Minimally invasive surgery (MIS), such as laparoscopy, has become popular due to shorter recovery times and less postoperative pain. However, recent evidence raises concerns regarding its use in cervical cancer, especially for larger tumors. While MIS shows advantages in early-stage tumors, studies suggest that traditional open surgery might offer better oncological outcomes in some cases (Xu et al., 2024)⁴. Radical trachelectomy, combined with pelvic lymph node dissection, has emerged as a fertility-preserving surgical option for patients with early-stage cervical cancer (IB1–IB2) with tumors smaller than 2 cm (Xu et al., 2024; Okonkwo, 2018).^{4,8}

More advanced surgeries, such as pelvic exenteration, are reserved for recurrent or extensive malignancies. Trachelectomy and cryosurgery also offer fertility-sparing alternatives, whereas laser surgery and hyperthermia provide localized tumor destruction with minimal systemic impact (Okonkwo, 2018).⁸

Radiation Therapy and Brachytherapy

Radiation therapy is widely used in conjunction with surgery, particularly in locally advanced or metastatic cases. External beam radiation, although effective, carries several side effects, including vaginal stenosis, bladder irritation, and premature menopause. Brachytherapy - the internal placement of radioactive sources - offers more targeted radiation delivery with reduced damage to surrounding tissues. This method has shown improved outcomes and decreased complications when compared to

conventional radiation techniques (Okonkwo, 2018).⁸

AI has significantly enhanced radiotherapy precision and planning. Adaptive radiotherapy, powered by AI, allows for real-time modifications to treatment based on imaging changes, leading to increased local control rates of over 80%. AI has also reduced planning time and optimized dose delivery, minimizing radiation exposure to non-target tissues by up to 20% (Paiboonborirak et al., 2025).¹⁶

Chemotherapy and Targeted Therapeutics

Chemotherapy remains fundamental in managing cervical cancer, particularly in advanced or metastatic stages. Agents like cisplatin, carboplatin, topotecan, and cyclophosphamide are commonly used. Combination therapies, especially those integrating cisplatin with paclitaxel or topotecan, have demonstrated improved patient outcomes (Kunkule et al., 2020).² However, systemic delivery of these agents often results in significant toxicity and off-target effects (Boon et al., 2022).²⁰

Targeted therapies have emerged to address these limitations. Bevacizumab, an anti-VEGF monoclonal antibody, has shown efficacy in restricting tumor angiogenesis. It is commonly administered in combination with standard chemotherapy and has become a first-line treatment for recurrent or metastatic cervical cancer. In cases where chemotherapy cannot be tolerated, single-agent bevacizumab serves as a second-line option (Xu et al., 2024).⁴

Immunotherapy and Novel Therapies

Immunotherapy represents a pivotal development in cervical cancer treatment. Immune checkpoint inhibitors (ICIs), antibody-drug conjugates (ADCs), and adoptive cell therapy (ACT) are being explored for their ability to harness the immune system in targeting tumor cells. These therapies offer promising results in cases resistant to conventional treatments (Xu et al., 2024).⁴

In addition to established modalities, novel drugs are being developed to inhibit angiogenesis and key oncogenic signaling pathways. These drugs aim to block the formation of new blood vessels essential for tumor growth, thus depriving the tumor of necessary nutrients (Okonkwo, 2018).⁸

Combination therapies are gaining traction due to their enhanced efficacy and reduced toxicity. The integration of chemotherapy with radiation, immunotherapy, or targeted drugs has shown superior outcomes. Notably, combinations like bevacizumab with cisplatin and topotecan have extended both progression-free and overall survival (D'Oria et al., 2022).²¹

Artificial Intelligence in Cervical Cancer Management

Artificial Intelligence (AI) is increasingly influencing all phases of cervical cancer treatment. In surgery, AI-enhanced robotic systems, such as the da Vinci Surgical System, have revolutionized operative precision. These systems minimize human error and improve outcomes in procedures like hysterectomies and lymph node dissections (Paiboonborirak et al., 2025).¹⁶

AI-assisted Optical Coherence Tomography (OCT) has also been integrated into surgical

workflows. Technologies like Full-Field OCT (FF-OCT) and Dynamic Cell Imaging (DCI) allow rapid, high-resolution intraoperative tissue analysis. These tools provide tumor margin assessments within minutes, improving surgical accuracy and reducing unnecessary tissue removal (Paiboonborirak et al., 2025).¹⁶

In radiotherapy, AI not only improves dose planning but also contributes to adaptive radiotherapy, adjusting treatment in real time based on anatomical changes. In chemotherapy, AI models can predict treatment response, facilitating more personalized regimens that maximize efficacy while reducing toxicity (Paiboonborirak et al., 2025).¹⁶

Future Directions and Considerations

The management of cervical cancer is increasingly shifting toward precision medicine, where treatment is tailored to individual tumor biology, patient genetics, and personal fertility preferences. As highlighted by Boon et al. (2022), current treatment options—though effective—often lack specificity and come with substantial systemic side effects. Future strategies must focus on enhancing tissue-targeting capabilities and minimizing adverse effects.²⁰

AI, novel drug development, and combination therapy approaches are expected to redefine the therapeutic landscape. The integration of immunotherapy and targeted treatments, guided by biomarkers and AI-powered diagnostics, holds promise for increasing survival while preserving quality of life.

FUTURE PERSPECTIVES AND RESEARCH GAPS IN CERVICAL CANCER

• Advancement in Precision Medicine

- Personalized diagnosis and therapy in cervical cancer now heavily depend on identifying molecular targets and predictive biomarkers.
- Despite rapid progress, the universal applicability of these biomarkers remains limited, presenting a major obstacle to patient selection and stratification in precision oncology (Xu et al., 2024).⁴

• Integration of Multi-Omics and High-Throughput Technologies

- Recent developments in high-throughput sequencing and bioinformatics have significantly improved the discovery of biomarkers relevant to early lesion detection, treatment response, and prognosis.
- Combining genomics, transcriptomics, and proteomics allows comprehensive tumor profiling to support individualized treatment strategies (Xu et al., 2024).⁴

• Single-Cell Technologies and Tumor Microenvironment (TME)

- Single-cell RNA sequencing (scRNA-seq) has facilitated a deeper understanding of the cervical cancer TME.
- Studies have identified neuro-like progenitor cells associated with radiotherapy efficacy, highlighting

- their potential role as predictive biomarkers.
- CRT has also been shown to induce innate immune activation and upregulate MHC-II expression in tumor cells, which supports recruitment of cytotoxic CD16⁺ NK cells and pro-inflammatory FCN1⁺ M-MDSCs—pointing toward a potential synergy between CRT and immunotherapy (Xu et al., 2024).⁴
- **Challenges in Screening and Vaccination**
 - Numerous public health challenges remain, including:
 - Development of cost-effective, point-of-care screening strategies
 - Establishing optimal screening intervals
 - Enhancing participation among women, especially in underserved regions
 - Strengthening healthcare infrastructure for screening, diagnostics, and treatment delivery
 - The use of novel biomarkers for triaging HPV-positive women also needs further investigation (Gupta et al., 2017).²²
 - The availability of low-cost HPV DNA testing could significantly improve screening algorithms in resource-limited settings (Gupta et al., 2017).²²
- **Equity and Access in the Global Context**
 - While affluent nations benefit from robust HPV vaccination and screening programs, disparities in access to preventive and therapeutic measures persist in low- and middle-income countries.
 - There is a strong need to expand research efforts in developing countries and marginalized populations to ensure equitable distribution of technological advances (Sekar et al., 2024).⁹
 - Digital health tools, artificial intelligence, and personalized screening algorithms are expected to transform care delivery, but successful implementation will require investment in infrastructure and training (Sekar et al., 2024).⁹
- **Emerging Technologies and Implementation Barriers**
 - Although novel technologies offer promise in improving the accuracy of cervical cancer prevention and early detection, their real-world application remains constrained by resource availability, time, and cost (Sekar et al., 2024).⁹
 - Transitioning from conventional screening to risk-based, biomarker-integrated strategies presents both opportunities and implementation challenges (Sekar et al., 2024).⁹
- **Advances in Radiotherapy (RT)**
 - High-precision external beam radiotherapy (EBRT), including stereotactic body radiotherapy (SBRT), is now being explored for patients ineligible for brachytherapy (BT).

- While SBRT offers a non-surgical alternative with better target coverage and reduced toxicity (e.g., to the rectum and bladder), it has been associated with inferior overall survival compared to BT in large cohort studies (Yamada et al., 2024).²³
- Retrospective analyses suggest that SBRT, especially using platforms like CyberKnife, may be safe and effective in selected patients not suitable for BT (Yamada et al., 2024).²³
- **Optimizing Dose and Exploring De-escalation**
 - Future research is needed to refine dose parameters for EBRT boosts and assess their long-term safety and efficacy.
 - Evidence now supports the feasibility of **dose de-escalation** in patients with low-risk features-such as squamous histology, tumor shrinkage >29%, and smaller tumor volume before BT-without compromising local control (Yamada et al., 2024).²³
 - This supports the move toward **personalized RT regimens** guided by prognostic markers and tumor characteristics.
- **Minimally Invasive and Individualized Treatment Approaches**
 - Technological advances have made cervical cancer treatment safer and more efficient.
 - Nonetheless, certain patients-particularly those with comorbidities or frailty-may not tolerate high-intensity treatment, underscoring the

need for **less invasive** yet effective therapeutic alternatives (Yamada et al., 2024).²³

- Future strategies must aim to broaden the scope of such treatment modalities while maintaining oncologic outcomes.

CONCLUSION

Cervical cancer remains a pressing global health challenge, particularly in low- and middle-income countries where access to screening and vaccination is limited. This review highlights the multifaceted approach required to combat the disease-from understanding its epidemiology and etiology to implementing effective prevention, screening, and treatment strategies. The pivotal role of HPV in cervical carcinogenesis underscores the importance of widespread vaccination and public education. Advances in molecular diagnostics, artificial intelligence, and minimally invasive therapies are transforming the landscape of cervical cancer management, offering more precise, personalized, and accessible care.

Despite these innovations, significant barriers persist, especially in resource-constrained settings. Bridging gaps in awareness, infrastructure, and policy implementation is essential to achieving the WHO's 2030 targets for cervical cancer elimination. Continued investment in research, technology, and equitable healthcare delivery will be critical in reducing the global burden of this preventable disease and ensuring that all women, regardless of geography, benefit from the progress made.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

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How to cite this article: R. Lalnunpuii, Mary V.J, Kamatchi.K. Current Trends and Future Directions in the Prevention, Screening and Management of Cervical Cancer - A Review. *International Journal of Research and Review*. 2026; 13(1): 104-118.
DOI: <https://doi.org/10.52403/ijrr.20260111>
