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Artificial Intelligence Enhanced Colposcopy Supports Early Detection of High Grade Cervical Intraepithelial Neoplasia in HPV Positive Individuals

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Abstract: *Cervical intraepithelial neoplasia (CIN) serves as a well-established precursor to invasive cervical cancer, particularly amongst individuals with persistent high-risk human papillomavirus (HPV) infection. Accurate and timely identification of high-grade CIN (CIN2+) is necessary for initiating appropriate clinical management and interrupting oncogenic progression. Conventional colposcopy, though widely utilized, remains constrained by substantial interobserver variability, inconsistent image interpretation, and limited diagnostic sensitivity—particularly in early-stage or subtle lesions. Artificial intelligence (AI)-augmented colposcopic platforms have emerged as a novel tool to enhance diagnostic precision by employing deep learning algorithms trained on large, expert-labeled datasets to recognize morphologic and vascular features associated with high-grade dysplasia. Convolutional neural networks (CNNs) have demonstrated the capacity to detect acetowhitening patterns, atypical vasculature, and lesion boundaries with higher consistency than standard visual assessment. Integration of AI-driven decision support into colposcopic workflows has been shown to improve the detection rates of CIN2+ in HPV-positive individuals, reduce variability across providers with differing levels of expertise, and lower the frequency of unnecessary biopsies in low-risk cases. Real-time AI interpretation also offers new avenues for clinical standardization, digital documentation, and remote diagnostic support in resource-limited settings. Despite promising performance metrics, widespread adoption requires rigorous external validation, algorithm retraining on diverse populations to prevent bias propagation, and clear clinical governance to ensure responsible use. AI-enhanced colposcopy marks a substantial progression in precision gynecologic diagnostics, with the potential to optimize current screening paradigms and triage pathways in the management of HPV-associated cervical disease.*

1. Introduction

Cervical cancer is the fourth most commonly diagnosed cancer and the fourth leading cause of cancer related death among women worldwide, with its impact being greater in low and middle income countries [1]. In 2022, there were 622,301 new cases of cervical cancer and 348,874 related deaths [2]. Persistent infection with high-risk human papillomavirus (HPV), particularly 16 and 18, account for approximately 95% of cervical cancer cases [3]. Other risk factors include smoking, multiple sexual partners and early initiation of sexual activity. HPV is a common sexually transmitted infection that many individuals clear on their own without any form of intervention. However, in a subset of patients, HPV remains in the cervical basal epithelial layers for several years, causing cellular changes that can manifest to premalignant lesions and ultimately progress to carcinoma [4]. Given these challenges, researchers are exploring new technologies, such as artificial intelligence (AI) to improve diagnostic accuracy for cervical cancer screening.

Despite being largely preventable, cervical cancer screening coverage remains limited in many low- and middle-income countries due to resource constraints and workforce shortages. Cervical intraepithelial neoplasia (CIN) represents a spectrum of histopathological changes in the squamous epithelium of the cervix, ranging from cellular atypia to severe dysplasia, and serves as a precursor to the development of malignant disease [5]. The precursor phase of cervical cancer, represented by CIN, can occur over a period of 10-20 years, during which patients are typically asymptomatic [6]. Colposcopy remains the standard diagnostic method for evaluation of premalignant lesions. The procedure involves applying acetic acid to the epithelium of the cervix, such that the abnormal epithelium will appear white suggesting areas of dysplasia or neoplasia [7]. Additional cervical cancer screening methods include Pap smears to evaluate cervical cytology, and HPV testing. The use of colposcopy is warranted in cases of high grade cytology, persistent low-grade cytology with positive high-risk HPV, or a positive HPV test for high risk strains [7]. Detection of CIN3+ in HPV-positive women is relatively high with a sensitivity of approximately 91%, while specificity is more modest at approximately 50%. Previous studies have also shown that sensitivity declines with increasing age and increases in patients with abnormal cytology [8]. This decrease in specificity can lead to unnecessary biopsies, while variation in colposcopist skill may lead to missed high-grade lesions. This suggests the need for tools that will enhance reliability and accuracy in clinical practice.

Traditional colposcopy is limited by interobserver variability, subjective interpretation and reduced reproducibility. These challenges have prompted the exploration of AI as a tool to enhance diagnostic accuracy and standardization. AI continues to be incorporated into medical practices at an exceedingly fast rate, with integration into diagnostic practices, clinical decision support, and image interpretation. Currently, there is a focus on the ability of AI to have a role in the detection of high-grade squamous intraepithelial lesion (HSIL) in HPV positive individuals, while simultaneously minimizing diagnostic error that is inevitable with human subjective decision making. AI-enhanced colposcopy analyzes cervical images, typically with use of a convolutional neural network (CNN), for features and morphological patterns that are consistent with different lesion grades, providing clinicians with real-time data that can inform further management of patients with cervical lesions [9]. This review aims to evaluate the efficacy and performance of AI-enhanced colposcopy in detecting HSIL in HPV-positive patients.

2. Artificial Intelligence and Machine Learning in Medical Imaging

Artificial Intelligence (AI) in medical imaging refers to the development of computer systems capable of performing tasks that traditionally require human intelligence, such as interpreting and learning from medical images to achieve specific diagnostic goals [10]. This makes AI systems relevant in medical specialities that rely on image interpretation. These systems use advanced algorithms to process complex imaging data, identifying subtle abnormalities with speed and consistency- significantly enhancing diagnostic accuracy and efficiency [10]. This helps with integration into clinical decision making, reducing interpretation variability among providers. An advantage of AI is the ability to handle vast amounts of image data, which enables it to detect patterns that may be overlooked by human experts. Machine learning (ML), which is a subset of AI, involves the use of algorithms that enable computers to learn from and make predictions based on data. In the context of medical imaging, ML algorithms are trained to identify patterns in images such as CT scans, MRIs, and X-rays [11].

Over time, these algorithms improve as they are exposed to more data, leading to more accurate diagnostic predictions. Unlike traditional image-processing methods, which rely on predetermined rules, ML systems adapt to the data they analyze, allowing them to identify new and potentially unforeseen patterns that could be critical for diagnosis [11]. This adaptability enhances diagnostic accuracy among different populations and imaging settings. The integration of AI and ML in medical imaging provides significant advantages. By utilizing these technologies, AI systems can identify subtle abnormalities in imaging data that may be difficult for the human eye to detect [12]. This advancement has helped set the stage for convolutional neural networks (CNNs), which have revolutionized pattern recognition in medical imaging.

3. Convolutional Neural Networks – Pattern Recognition Powerhouses

Modern advances in AI for image analysis are largely driven by deep learning, especially Convolutional Neural Networks (CNNs). A CNN is a type of artificial neural network specifically well-suited for image recognition tasks. Its architecture is inspired by the human visual cortex and consists of multiple layers of interconnected ‘neurons’ that automatically learn to detect features in images [13]. This structure allows CNNs to mimic human pattern recognition, helping detect features critical for diagnosis. Each convolutional layer applies numerous small filters (kernels) that scan the image to detect specific visual patterns such as edges, textures or colors [13]. Through a hierarchical system, simple features detected in early layers (like edges or blobs) combine into more complex features in deeper layers – such as shapes or specific tissue patterns. In summary, CNNs learn to recognize patterns in a data-driven way; they develop internal feature detectors that respond to clinically relevant cues in images without being explicitly programmed to do so [13]. This ability to automatically learn and compose features makes CNNs extremely powerful for pattern recognition and object detection in medical images, specifically colposcopy-based detection of CIN. CNNs enhance accuracy and consistency in cervical cancer screening and diagnosis.

4. CNN Training And Application to Colposcopic Images

Building a convolutional neural network for medical-imaging tasks begins with a large corpus of well-annotated images whose labels (e.g., lesion grade, tissue type, pathology result) serve as ground truth. During supervised learning, the network's millions of weights are iteratively updated via back-propagation to align its predictions with the labeled outputs. In medicine, fully labeled medical datasets are scarce. To address this, developers use data-augmentation techniques such as random image rotations, flips, and color adjustment to expand the dataset [14]. This introduces variability, helping the model generalize to unseen data. To strengthen the model, cross-validation techniques are used to monitor for over-fitting with metrics such as area under the receiver operating characteristic (ROC) curve (AUC) and Cohen's kappa coefficient [15]. Recent meta-analyses show that, once trained on sufficient data, deep-learning models routinely meet or even surpass clinician accuracy in image-based cancer diagnostics, including cervical applications [16]. This consistent outperformance of clinician accuracy reinforces the potential of artificial intelligence as a reliable diagnostic tool in clinical practice.

In colposcopy, convolutional neural networks are trained to recognize morphologic and vascular features associated with cervical intraepithelial neoplasia (CIN). For example, a landmark study by Yuan et al. (2020) trained a CNN on over 22,000 biopsy-confirmed colposcopic images and reported an AUC of 0.93 in detecting high-grade lesions, outperforming expert colposcopists on the same dataset [12]. This suggests that CNNs can accurately detect high grade lesions, improving consistency and reliability. Building on this, Kim et al. incorporated a segmentation branch into their CNN that identified acetowhite regions—raising the model's high-grade squamous intraepithelial lesion (HSIL) detection accuracy from 70% to approximately 76%, matching or exceeding experienced clinician performance [17]. Other deep learning approaches have expanded this further, enabling models to segment entire lesion boundaries and detect atypical vascular patterns (e.g., mosaicism, punctuation) with pixel-level accuracy [17].

These tools not only improve diagnostic sensitivity but also provide visual overlays that support clinician decision-making in real time. Taken together, CNN training principles—when applied to high-quality colposcopic datasets—can translate into clinically meaningful tools that enhance diagnostic accuracy, reduce observer variability, and improve biopsy targeting in HPV-positive women undergoing evaluation for high-grade CIN.

5. Training And Performance In Colposcopy – Recent Studies

In the last five years, several notable studies have demonstrated the performance of artificial intelligence, particularly convolutional neural network models, in improving colposcopy diagnostics. In a 2020 study, Hu et al. developed an automated visual evaluation CNN by using thousands of digitized cervical images and reported high accuracy in detecting cervical precancer [19]. This model achieved an area under the receiver operating characteristic curve (AUC) of approximately 0.91 for identifying high-grade cervical intraepithelial neoplasia (CIN), substantially outperforming human experts' visual assessments who had an AUC of approximately 0.69. This high AUC suggests that these models can provide expert level interpretation of images, limiting the need for expert colposcopists especially in regions with limited access. Furthermore, the AI system also surpassed the performance of conventional Pap cytology within the same cohort, underscoring the potential of deep learning to improve early detection [19]. In a 2022 study, Kim et al., evaluated the impact of combining image segmentation with CNN classification to improve colposcopy image analysis [17]. Researchers found that when the CNN was provided with a segmented acetowhite region, its accuracy in detecting high-grade lesions increased to approximately 75%-76%. This performance exceeded the level of experienced colposcopists who achieved 70% range on the same data set [17]. These findings suggest that incorporating colposcopy findings, such as acetowhite epithelium, can enhance the algorithm of the model, ultimately strengthening clinical parameters. Additionally, deep learning systems that incorporate dual modalities such as acetic acid and adjunctive iodine-stained images have reported similar results. In one study, these models have achieved a sensitivity of approximately 85% and a specificity of 83% in classifying cervical lesions, matching expert examiners [17]. These studies collectively indicate that AI can not only match expert colposcopic evaluation, but exceed in diagnostic accuracy especially in consistency, speed, and sensitivity in the detection of CIN2+.

6. Clinical Applications, Benefits, Limitations

Artificial intelligence (AI)- assisted colposcopy enhances standard colposcopy by integrating a deep learning model that analyzes colposcopic images in real time, helping clinicians identify high- grade cervical intraepithelial neoplasia before biopsy. The procedure starts with image analysis which is done with deep learning through the use of CNNs and the U-Net model. The cervix is visualized and cropped with the CNN. The U-Net model then searches for suspicious lesions in the segmented areas. If an area is thought to be suspicious by the U-Net model, low-grade or higher, the findings are flagged.

These findings are incorporated and overlaid with findings from the human colposcopist as a means of providing a second checkpoint to positive screening. AI also assists in guidance of biopsy regions by marking on the image where a biopsy should be taken [20]. The overarching concept is that AI-guided colposcopy should complement colposcopists rather than replace them [21]. Human colposcopists remain responsible for the final diagnosis [22]. AI-assisted colposcopy was developed to be used in clinical practice as a way to standardize colposcopic assessment and biopsy procedures. In clinical practice, the outcome of colposcopy guided biopsy is dependent solely on the skill and experience of the clinician, which can result in variability of the detection of high-grade neoplasia. By integrating AI with human expertise, studies have shown improved sensitivity in the detection of cervical intraepithelial neoplasia (CIN) [20]. This helps provide more consistent and reliable results for diagnosis. The usage of AI assistance has shown to reduce interobserver variability, providing a more consistent basis for diagnosis. By using the neural network model, the lesions being studied are enhanced by labeling the extent of abnormal areas [23].

This helps in obtaining accurate detection of CIN and also reduces unnecessary biopsies and the chance of missing high-grade lesions [23]. In conjunction, AI acts as a “second set of eyes” to provide objective results in colposcopy assessments [23]. This feature is valuable in LMICs where there is a shortage of experienced clinicians [20]. AI can be a helpful tool in these regions with limiting training opportunities to ensure high detection of CIN [23]. Incorporating AI into cervical cancer screening can help expand access to all individuals, especially those in underserved regions.

7. Advantages

AI-assisted colposcopy offers several significant advantages in resource-limited settings, specifically in low and middle income countries (LMICs) [22]. These regions have a shortage of skilled colposcopists and cytopathologists [22]. AI systems resolve this problem by enhancing diagnostic performance without the need for colposcopists [24]. In addition, AI assistance can enhance clinical decision making on whether a punch biopsy or more specialized care is needed, reducing diagnostic uncertainty [22]. AI assistance is useful for confirmation of sampling along with localization [25]. Furthermore, AI-assisted colposcopy can be a more affordable option when compared to cytology or HPV testing. The latter fords of testing require expensive equipment and large laboratory infrastructures [25]. AI can support screening programs in LMICs, potentially solving the problem of being short of well-trained personnel within a shorter time interval [25]. By improving diagnostic precision and reducing costs, AI-assisted colposcopy can be implemented in underserved populations to support accessible cervical cancer screening.

8. Limitations

Despite the many benefits, several limitations remain in AI-assisted colposcopy. A major concern is that there are many studies that rely on samples from a single institution, which may introduce bias and reduce generalizability [22]. To address this, future research should include data from multicenter institutions with a wide range of demographics. Expanding diversity among the patient pool will enhance applicability across different settings [22]. A fundamental ethical bias exists among the algorithms used for training AI models. Many models are developed with datasets reflecting certain ethnic, racial, gender and age demographics. This can introduce biases leading to diagnostic inequity. To address this, further refinement is necessary to require training data to be broadly representative across different ethnic, racial, gender, age and other groups [27].

Study design is another limiting factor. Most of the current literature is based on retrospective studies. While these studies showcase promising results, prospective clinical trials are needed to validate the performance of AI models [22]. Assessing AI accuracy in controlled lab environments may not accurately predict its performance in diverse, real-world clinical settings. These prospective trials should be human-centered and include a deployment environment [28]. In addition, algorithmic bias is a significant ethical concern and can be a limiting factor in AI-assisted colposcopy. It can arise from incomplete or erroneous training data and may lead to new forms of discrimination or systemic inequalities. This includes algorithms relying on non-lesion features like annotations or rulers in images or drawing spurious correlations based on patient race. Users are also subject to cognitive biases and put more trust in AI which can lead to missed errors or misuse of the technology [28].

Implementing AI tools poses additional logistical and financial challenges. Significant costs are associated with deploying AI tools, including the technology itself, training staff, time, and compatibility with existing systems. These costs can be substantial and may limit implementation, particularly in less developed countries. If large organizations can only afford these tools, they may not effectively address health inequalities [27]. AI-assisted colposcopy requires a well-organized infrastructure [22]. Integrating AI systems into clinical workflow can be challenging and may impact performance [28]. Determining responsibility when an AI-assisted diagnosis is inaccurate is a concern. Patient privacy and confidentiality are also significant challenges with data usage [21].

Additionally, the lack of standardized imaging protocols still exists and equipment across different practices affects the reliability and generalizability of AI models trained on diverse data sources [21]. There can be resistance to incorporating AI among health professionals and lack of adequate training for clinicians in using and interpreting AI outputs, or in identifying conditions that AI may miss, is a limitation [28]. Many AI models, particularly deep learning networks, are considered "black boxes" as their decision-making processes are blocked to humans [21].

This lack of transparency and explainability can raise concerns about the accuracy and validity of results from a clinical and patient perspective and may hinder user trust or effective human oversight. There are also concerns that increased dependence on AI technology assistance can decrease the clinical skill set of the colposcopists over time [21]. Addressing these limitations are essential to providing access for AI-assisted colposcopy to aid in cervical cancer screening.

9. FUTURE DIRECTION

Further research is needed to continually refine and train systems to enhance their performance, especially in recognizing subtle features. Improving accuracy, specificity, and positive predictive value (PPV) may garner access to higher quality colposcopy images and more advanced algorithms [22]. Novel techniques and algorithms are necessary to reduce the impact of data scarcity in evaluating and predicting clinical outcomes [26]. Further studies are needed to compare conventional techniques with the AI model across different patient populations.

In addition, AI models must be trained to analyze time-sensitive colposcopic images, and algorithms must be refined to detect neoplastic changes amid other cervical pathologies [21]. By training these models to decipher complex data, it will help further optimize clinical decision making among different patient populations. Additionally, collecting data from different medical institutions can enhance the diversity of samples and address potential bias from single-center institutions. Future research should also include additional patient history such as smoking, age of when sexual intercourse first began, and number of sexual partners [21].

Furthermore, additional research should aim to apply AI models to clinical practice to specifically address the role of AI in predicting cervical cancer outcomes [22]. Future applications might also extend beyond screening and diagnosis to include cancer treatment, prognosis prediction, and prevention [24]. Integrating AI systems into local colposcopy clinics to support colposcopists is also a possible future direction. For this to occur, AI should be made feasible, reliable, and less expensive for clinical use to allow for greater accessibility. Insurance coverage for AI services could also reduce financial barriers for patients and help with accessibility [21].

However, current regulatory frameworks face challenges in addressing the novel risks of AI, particularly with adaptability, autonomy, bias, and opacity. Further guidance is needed to focus on disclosing risks to patients and ensuring that benefits are clearly translated [28]. In addition, mandatory requirements like including minority data should be considered to address algorithmic bias and define appropriate AI evaluation to reduce bias. Nevertheless, implementing pilot programs can help provide insight to the feasibility of AI-assisted colposcopy [27]. Regulatory adaptation is recommended to include underrepresented populations in training models to minimize bias and health disparities [28].

Consequently, clinician training must also be considered when using artificial intelligence technology. Many healthcare professionals remain hesitant to use models because of limited training with such models. Addressing these concerns through proper training and transparent communication can help build trust and safety when using AI tools in clinical settings [21]. The successful integration of AI-assisted colposcopy into clinical practice depends on addressing limitations, refining frameworks, ensuring equal access and investing in clinician training to advance cervical cancer screening and accessibility for all populations.

10. Conclusion

Artificial Intelligence holds substantial promise in enhancing colposcopy by supporting the detection of cervical cancer during routine screenings. Through its ability to recognize patterns associated with dysplasia, AI may offer improvements in diagnostic accuracy and consistency compared to individual clinicians alone. This technology can help not only reduce unnecessary biopsies in cases of benign or low-risk lesions, but also minimize provider-to-provider variation. Moreover, AI could play a transformative role in expanding access to high-quality cervical cancer screening, particularly in under-resourced settings or regions with limited specialist availability.

Despite these advantages, further investigation is essential to validate AI's effectiveness across diverse populations before widespread clinical adoption. Equally important is ensuring that AI applications in healthcare are implemented ethically and responsibly. With appropriate safeguards, AI has the potential to enhance early detection efforts and contribute meaningfully to cervical cancer prevention.

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