International Journal of Pharmaceutical and Bio-Medical Science

ISSN(print): 2767-827X, ISSN(online): 2767-830X

Volume 06 Issue 05 May 2026

Page No : 1014-1021

DOI: https://doi.org/10.47191/ijpbms/v6-i5-06, Impact Factor: 8.428

The Role of Artificial Intelligence in Oral Cancer: A Review of Current Applications and Future Directions

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ABSTRACT

Oral cancer remains a major global health concern with high morbidity and mortality, largely due to delays in detection and challenges in accurate diagnosis. Traditional methods such as visual examination, biopsy, and histopathological review can be time-consuming, subjective, and limited by clinician experience. In recent years, artificial intelligence has shown promise in improving the accuracy and efficiency of oral cancer care. Deep learning models support early detection by identifying suspicious lesions on clinical photographs and histopathology images, while digital pathology systems help reduce inter-observer variability. AI-based tools are also contributing to risk assessment, prognosis prediction, and treatment planning, including radiotherapy dose optimization and surgical margin evaluation. Mobile health applications and wearable devices enhance patient monitoring and support long-term follow-up by identifying changes that may indicate recurrence. Despite these advances, concerns related to data quality, model transparency, privacy, and regulatory approval remain barriers to widespread adoption. Looking ahead, integrating imaging, clinical data, and molecular information may enable more personalized treatment strategies. With careful clinical validation and responsible implementation, AI has the potential to complement clinician judgment and improve outcomes across the oral cancer care continuum.

KEYWORDS: Artificial intelligence; Oral cancer; OSCC; AI tools; deep learning; digital pathology; precision medicine

ARTICLE DETAILS

Published On: **06 May 2026**

Available on: **https://ijpbms.com/**

1. INTRODUCTION

Oral cancer is one of the most common malignancies worldwide, with more than 350,000 new cases and over 170,000 deaths reported annually, making it a significant contributor to the global cancer burden (Sung et al., 2021). The incidence is particularly high in South and Southeast Asia, where tobacco, alcohol, and betel nut consumption are major risk factors. Despite improvements in treatment modalities, survival rates for oral cancer remain modest, with five-year survival hovering around 50–60 % in many regions (Rivera, 2022). A major reason for this poor outcome is delayed diagnosis—most patients present at advanced stages, when prognosis is considerably worse.

Conventional diagnostic approaches, including visual oral examinations, tissue biopsies, and histopathological interpretation, have critical limitations. Visual inspection alone often misses early or subtle lesions, while biopsy procedures are invasive, resource-intensive, and can be delayed by logistical barriers. Even histopathology, the current gold standard, is subject to inter- and intra-observer variability, leading to inconsistent grading and risk assessment (Bianchi et al., 2024). These shortcomings underline the urgent need for reliable, efficient, and accessible tools for earlier and more accurate detection of oral cancer and its precursors.

In recent years, artificial intelligence (AI) has emerged as a transformative technology in healthcare, particularly within oncology. Deep learning (DL) and machine learning (ML) models have shown high accuracy in analyzing medical images, pathology slides, and clinical datasets, with applications ranging from cancer detection to prognosis and treatment planning. In oral cancer specifically, AI has demonstrated promise in identifying potentially malignant disorders, differentiating tumor subtypes, and even predicting survival outcomes (Awan et al., 2022; Wang et al., 2023).

The purpose of this review is to provide an updated overview of AI applications in oral cancer, examining its role in early detection, risk assessment, treatment planning, pathology, and patient monitoring. In addition, the review highlights the current limitations of AI systems, including data quality, ethical challenges, and clinical integration and explores future directions that may enable responsible and effective use of AI in oral oncology.

2. INTRODUCTION OF ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) refers to the ability of computer systems to perform tasks that traditionally require human intelligence, such as recognition, prediction, and decision-making. Within healthcare, the most commonly applied branches are **machine learning (ML)** and **deep learning (DL)**. ML involves algorithms that learn from data patterns to make predictions, while DL, a subset of ML, uses artificial neural networks with multiple layers to process complex and high-dimensional inputs such as medical images and genomic data (Topol, 2019).

Convolutional neural networks (CNNs), in particular, excel at image classification and segmentation, and they have been widely adopted in cancer detection and grading (Esteva et al., 2021). Other models such as support vector machines (SVMs), random forests, and ensemble methods are also used for classification of patient risk profiles and survival prediction, often with strong performance in smaller datasets (Yu et al., 2022).

Natural language processing (NLP) is another important domain of AI, applied in oncology to extract clinically meaningful information from electronic health records, pathology reports, or even patient narratives. Integrating NLP with structured clinical data can improve patient Tstratification and guide treatment decisions (Liu et al., 2022).

The main advantages of AI in medicine are its ability to handle vast, heterogeneous datasets and to uncover subtle patterns that may be imperceptible to human observers. However, its limitations are equally important to note. AI models are highly data-dependent, often requiring large, annotated, and diverse datasets for robust training. They may also function as "black boxes," with limited interpretability of how predictions are generated, which can limit clinician trust and adoption.

Understanding these fundamentals is essential before examining how AI is being applied specifically in oral cancer, from early detection and histopathology to treatment planning and follow-up.

3. AI in Early Detection and Diagnosis of Oral Cancer

Early detection of oral cancer is critical, as prognosis significantly declines with disease progression. Despite advances in clinical practice, many patients are still diagnosed at advanced stages due to the subjective nature of visual examinations, delays in biopsy, and inter-observer variability in histopathology. Artificial intelligence has shown great promise in addressing these gaps by enabling objective, reproducible, and rapid assessment of clinical and imaging data.

Image-based detection is the most extensively studied application of AI in oral oncology. Deep learning models, especially **convolutional neural networks (CNNs)**, have demonstrated high accuracy in analyzing intraoral photographs, radiographs, and histopathological slides (Fig. 1). For example, CNNs trained on large annotated image datasets have been able to classify potentially malignant disorders such as **leukoplakia and erythroplakia**, as well as distinguish early oral squamous cell carcinoma (OSCC) from benign lesions, with performance often comparable to expert clinicians (Sastry et al., 2020; Yang et al., 2022).

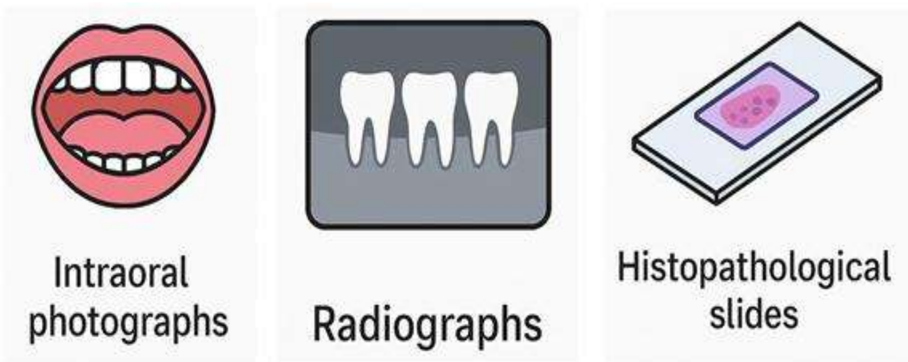

Figure 1. Convolutional Neural Networks (CNNs) can analyze intraoral photographs, radiographs and histopathological slides with higher accuracy.

AI has also been integrated into **digital pathology**, where whole-slide imaging combined with DL algorithms enables automated detection of dysplasia and malignant transformation. These systems can not only identify abnormal regions but also quantify architectural and nuclear features that may be overlooked in routine examinations, thereby reducing inter-observer variability (Lu et al., 2021). Mobile and point-of-care applications are also emerging.

Smartphone-based AI tools have been developed to analyze intraoral images in real time, allowing for screening in low-resource settings where access to specialists is limited. Such tools could potentially transform community-level cancer surveillance and improve early case detection (Fu et al., 2020).

Overall, AI-based diagnostic approaches show high sensitivity and specificity for early lesion recognition and risk stratification (Fig. 2). While these systems are not yet replacements for biopsy, they can serve as valuable adjuncts to clinical examination, improving diagnostic confidence and facilitating timely referral and treatment.

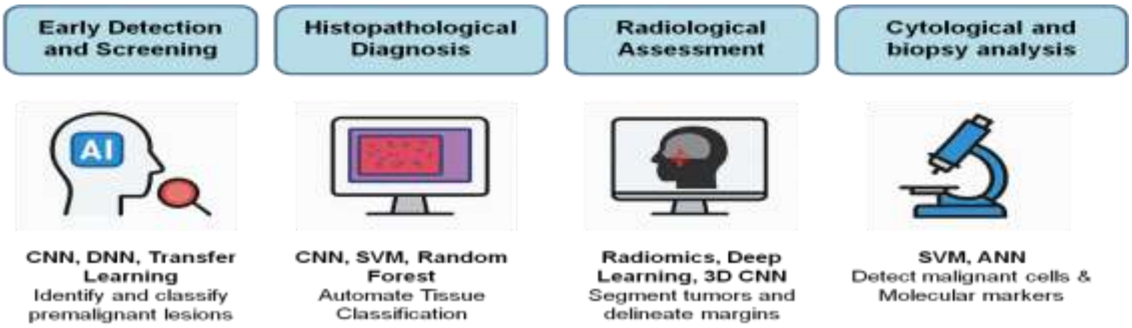

Figure 2. Flow diagram depicting the application of ML models in detection, diagnosis, treatment and prognosis of oral cancer.

4. AI IN RISK ASSESSMENT AND PROGNOSIS

Artificial intelligence has shown growing value in predicting clinical outcomes for patients with oral cancer by analyzing large datasets that include demographic, clinical, and pathological features. Machine learning (ML) models can identify subtle patterns associated with disease progression, making them useful for **risk stratification**. These tools help clinicians estimate the likelihood of aggressive disease at the time of diagnosis and support decisions about treatment intensity. Several recent studies using ML approaches have achieved accuracies above 80 % when predicting high-risk profiles and early disease progression in oral squamous cell carcinoma (OSCC) based on clinical and demographic inputs (Zhang et al., 2021).

One area where AI has been particularly successful is in predicting lymph node involvement, recurrence, and survival outcomes. Deep learning models trained on histopathological image features and clinical variables have demonstrated strong performance in identifying patients at risk of recurrence and metastasis, with reported area-under-curve (AUC) values often greater than 0.85 (Zhu et al., 2022). Automated analysis of lymphovascular invasion patterns using digitized slides has also been shown to improve prediction of regional metastasis, reducing subjectivity in traditional assessments (Qin et al., 2021). Beyond this, AI-assisted radiomics—quantifying imaging features from CT and MRI scans—has been explored extensively for forecasting survival, with encouraging accuracy and reliability in multi-center cohorts (Lai et al., 2023).

The integration of AI with **genomic and biomarker datasets** represents another promising advancement. By analyzing gene expression profiles, proteomic signatures, and microRNA patterns, ML models have been able to stratify OSCC patients into molecular risk categories that outperform traditional staging methods (Lin et al., 2021). Multi-omics models combining genomic alterations, histology, and clinical variables have shown improved predictive power for recurrence-free survival and distant metastasis, suggesting that AI can help capture biological complexity more effectively than single-variable approaches (Song et al., 2023). Biomarker-driven AI tools are also being developed to identify high-risk premalignant conditions before malignant transformation, offering opportunities for earlier intervention (Wang et al., 2022).

Taken together, these advances highlight the potential of AI to improve prognostic precision, support individualized treatment planning, and contribute to earlier detection of disease recurrence. As datasets grow and become more standardized, AI-based prognostic systems may become important clinical decision-support tools in oral oncology.

5. AI IN TREATMENT PLANNING AND PRECISION MEDICINE

Artificial intelligence is playing an increasingly important role in improving treatment planning for oral cancer. One area of interest is **surgical margin analysis**, where complete tumour removal is key to reducing recurrence. Intraoperative assessment can be subjective and time-consuming, and AI-based imaging tools are being explored to support real-time margin evaluation. Recent work in head and neck oncology shows that AI can help identify residual tumour tissue more reliably and may reduce the need for frozen sections in selected cases (Peltonen et al., 2024; Mukul et al., 2025).

AI is also being integrated into **radiotherapy planning**, a process that requires complex contouring of target volumes and nearby organs. Deep learning models can automate segmentation and predict optimal dose distributions, reducing planning time and standardizing quality across institutions. Several studies have shown that automated contouring can achieve clinically acceptable accuracy and outperform **manual approaches in consistency (Robotti et al., 2023; Van Dyk et al., 2022). AI-supported systems are also being**

evaluated for adaptive planning to account for anatomical changes during treatment (Fig. 3)

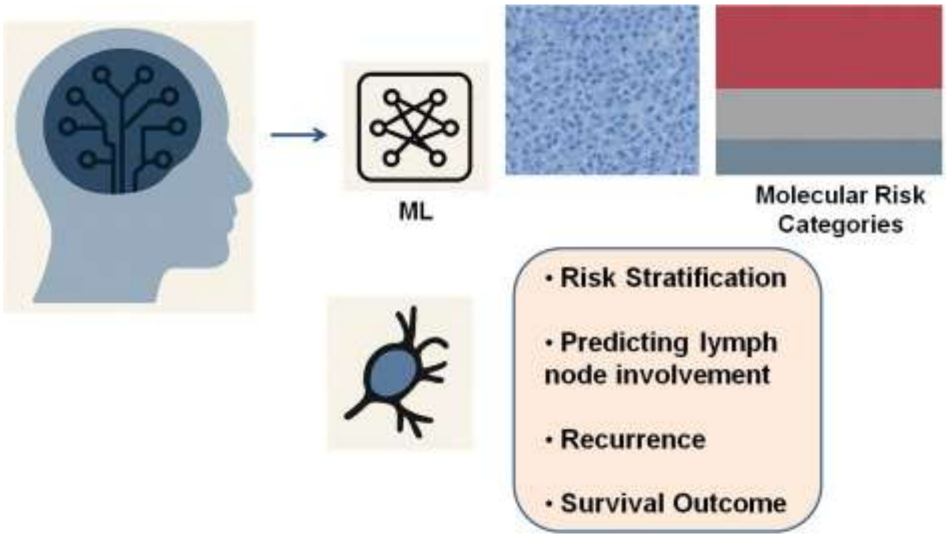

Figure 3. Machine learning (ML) models can identify subtle patterns associated with disease progression.

In systemic therapy, predictive models are being developed to estimate treatment response and identify patients at higher risk of toxicity, supporting more personalized chemotherapy regimens. Although this remains early in oral oncology, progress in broader head and neck cancer suggests these tools could soon be clinically relevant.

AI is further influencing robotic surgery and augmented reality, where enhanced visualization and navigation can improve surgical precision in the confined anatomy of the oral cavity. Early reviews suggest potential benefits in operative efficiency and margin visualization, although most evidence remains preliminary (Peltonen et al., 2024; Kandasamy et al., 2025). As these systems mature, AI-driven guidance may support complex dissections and reconstruction planning.

6. AI IN PATIENT MONITORING AND FOLLOW-UP

Long-term monitoring is essential in oral cancer care because many patients experience delayed complications, persistent functional problems, or locoregional recurrence. Artificial intelligence is increasingly being used to support outpatient follow-up through **mobile health applications** that track symptoms, capture patient-reported outcomes, and send reminders for appointments or rehabilitation tasks. These tools can help identify concerning changes earlier and improve adherence to scheduled reviews (Kim et al., 2021). **AI-enabled wearables** add continuous physiological monitoring, including activity levels, sleep patterns, and speech metrics. In head and neck cancer populations, these data streams have been used to assess treatment toxicity, functional recovery, and quality-of-life trends (Gupta et al., 2022). More advanced applications use time-series modeling to detect subtle deviations from a patient's baseline and predict recurrence risk before clinical manifestation. Deep learning models trained on longitudinal clinical, imaging, and biomarker data have demonstrated encouraging accuracy in early recurrence prediction in head and neck cancer cohorts (Kong et al., 2020; Wen et al., 2023). By integrating passive and active monitoring channels, AI-based systems have the potential to support personalized survivorship planning, decrease unplanned hospital visits, and flag high-risk patients who need expedited clinical assessment. However, concerns remain regarding data privacy, user adherence, and the need for prospective validation before routine adoption.

7. Challenges and Limitations

Despite rapid progress, several challenges limit the routine use of artificial intelligence in oral cancer care. **Data quality** remains one of the most important barriers. Many AI models are trained on small, single-center datasets that lack demographic diversity, increasing the risk of overfitting and limiting generalizability. In digital pathology, for example, variability in staining, scanner resolution, and annotation quality can negatively affect model performance (Abdelrahman et al., 2023). **Ethical concerns** are also prominent. Models may inherit biases from skewed training sets, potentially disadvantaging specific age groups or underserved populations. Privacy concerns arise when sensitive clinical and imaging data are stored or shared, and patients must be properly informed about how their data are used (Vokinger et al., 2021). **Regulatory barriers and clinical validation** slow adoption, as many AI systems lack prospective, multi-institutional trials to demonstrate safety and effectiveness in real-world settings. Regulatory agencies emphasize transparency, explainability, and continuous performance monitoring, but most available models still function as "black boxes" (Kelly et al., 2019; Gerke et al., 2020). Finally, the **integration of AI into clinical workflows** remains difficult. Clinicians may be hesitant to rely on algorithmic predictions, training requirements are significant, and interoperability between hospital information systems and AI platforms can be limited. Acceptance tends to improve when AI is framed as a decision-support tool rather than a replacement for clinical judgment (Rajpurkar et al., 2022). Addressing these challenges will require interdisciplinary collaboration, carefully curated datasets, and robust regulatory frameworks (Table 1)

Table 1. Summary of Artificial Intelligence Applications in Oral Cancer Diagnosis, Prognosis, and Management

AI Application Area	AI/ML Techniques Used	Data Type / Modality	Purpose / Outcome	Key Findings / Advantages	Limitations / Challenges	References
Early Detection and Screening	CNN, Deep Neural Networks (DNN), Transfer Learning	Oral lesion images, autofluorescence, hyperspectral imaging	Identification and classification of premalignant and malignant lesions	High diagnostic accuracy (>90%); non-invasive; assists in screening in low-resource settings	Requires large annotated datasets; variability in image quality	Li et al., 2024
Histopathological Diagnosis	CNN, SVM, Random Forest	Digital histopathology slides (H&E stained)	Automated tissue classification, feature extraction, grading	Rapid and reproducible diagnosis; reduces inter-observer variability	Data standardization; generalization across labs	Kim et al., 2022; Albalawi et al., 2024.
Radiological Assessment (CT/MRI/PET)	Radiomics, Deep Learning, 3D CNN	Radiographic images (CT, MRI, PET-CT)	Tumor segmentation, margin delineation, staging	Accurate tumor boundary identification; supports surgical planning	Requires multi-modal image integration; computational cost	Yuan et al., 2024
Cytology and Liquid Biopsy Analysis	SVM, Random Forest, ANN	Cytology images, circulating tumor DNA (ctDNA), microRNA data	Automated detection of malignant cells and molecular markers	Improves early, non-invasive diagnosis; potential for screening	Needs robust data preprocessing; validation in large cohorts	Sunny et al., 2019
Prognosis and Risk Prediction	Logistic Regression, Ensemble Models, Deep Learning	Clinical and genomic data, lifestyle factors	Predicting recurrence, survival, treatment response	Personalized risk stratification; supports clinical decision-making	Heterogeneous data integration; model interpretability	Kim et al., 2019
Treatment Planning and Response Monitoring	Reinforcement Learning, Predictive Modeling	Radiomic, genomic, and clinical data	Optimizing radiotherapy dose, chemotherapy regimen prediction	Enables adaptive therapy and individualized treatment	Limited by lack of real-time clinical data	Veeraraghavan et al., 2024
Telemedicine and AI-Driven Screening Apps	Mobile-based CNN, Cloud AI	Smartphone-captured oral images	Point-of-care screening, remote diagnosis	Increases accessibility and early detection in rural areas	Data privacy and image quality concerns	Schmidl et al., 2025

Pathway and Drug Target Identification	Deep Learning, Network Analysis	Omics datasets (transcriptomics, proteomics, metabolomics)	Identifying novel biomarkers and therapeutic targets	Accelerates discovery of molecular pathways; supports drug repurposing	Limited labeled datasets,Data quality and heterogeneity &AI lack biological interpretability	Schomberg et al., 2019

8. FUTURE PERSPECTIVES

As artificial intelligence continues to evolve, its role in oral cancer care is expected to shift toward collaborative decision support rather than replacement of clinical expertise. Emerging studies emphasize that AI performs best when paired with clinician judgment, improving diagnostic confidence and reducing variability while preserving human oversight (Rajpurkar et al., 2022). Another promising direction is the integration of **multi-modal data**, combining imaging, genomics, histopathology, and clinical information within unified models. By capturing the biological complexity of oral cancer, multi-modal deep learning can refine risk stratification, predict treatment response, and support early detection of recurrence (Huang et al., 2020). This approach also aligns with advances in **personalized oncology**, where AI can identify molecular signatures, guide targeted therapy selection, and tailor radiotherapy dosing strategies based on tumorbehavior (Liu et al., 2023). Federated learning and privacy-preserving analytics offer additional opportunities by enabling institutions to train models collaboratively without centralizing patient data (Rieke et al., 2020). Ultimately, integrating AI platforms into routine workflows could enable more efficient surveillance, streamlined treatment pathways, and individualized survivorship plans. To realize this potential, future work must focus on robust clinical validation, transparent model outputs, and user-friendly interfaces that encourage adoption. With continued collaboration between clinicians, engineers, and regulators, AI-assisted systems are positioned to support safer and more personalized oral cancer care.

9. CONCLUSION

Artificial intelligence is becoming an important support tool across the oral cancer care pathway. It can assist in early detection by helping identify suspicious lesions on clinical images and histopathology slides, offering greater consistency than visual examination alone. In digital pathology, AI may reduce inter-observer variability and highlight features that can be difficult to detect during routine review. Within treatment planning, AI can improve radiotherapy contouring accuracy, assist with surgical margin decisions, and help guide dose optimization. Mobile health platforms and wearable devices also extend monitoring outside the clinic, supporting follow-up, symptom tracking, and earlier recognition of recurrence.

Despite these promising advances, challenges remain. Data quality, privacy concerns, and regulatory approval continue to slow clinical adoption. Many models still lack transparent explainability, making it difficult for clinicians to fully trust automated recommendations. Successful integration will require interoperability with clinical systems, user-friendly interfaces, and proper training for healthcare teams. Looking forward, combining imaging, clinical data, and molecular information may allow AI to support more personalized care. With careful validation, ethical safeguards, and close collaboration between clinicians and developers, AI has the potential to improve diagnostic accuracy, streamline workflows, and support individualized treatment decisions without replacing clinical expertise.

ACKNOWLEDGEMENT

JR acknowledges Department of Health Research (DHR, ICMR) New Delhi for DHR Women Scientist fellowship (no.R.12013/35/2024-HR).

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