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Review Article

From pixels to prognosis: Application and challenges of artificial intelligence in oral disease diagnosis

Priyanshi Mathur[1], Sunira Chandra[1], Payal Tripathi[1], Shruti Sinha[1], Tanmay Srivastava[1]

[1]Department of Oral Medicine and Radiology, Saraswati Dental College and Hospital, Lucknow, Uttar Pradesh, India.

***Corresponding author:**
Priyanshi Mathur,
Department of Oral Medicine and Radiology, Saraswati Dental College and Hospital, Lucknow, Uttar Pradesh, India.

drpriyanshimathuromr@gmail.com

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ABSTRACT

Background: Early and accurate diagnosis of oral diseases is essential for effective treatment, but traditional methods can be subjective and time-consuming. Artificial intelligence (AI) offers potential improvements. This review examines the applications and challenges of AI in oral disease diagnosis.

Objective: The objective of this study was to comprehensively review the applications of AI and machine learning (ML) in oral disease diagnosis, focusing on algorithms, diverse applications, and challenges, particularly within the Indian healthcare context.

Method: An electronic search was conducted using the PubMed database, focusing on peer-reviewed articles published up to February 2025, using the keywords "Artificial Intelligence," "Machine Learning," and "Oral Disease Diagnosis," which resulted in 15,554, 12,661, and 6,867 items, respectively. After a thorough review, relevant data from other electronic sources were also included for additional information.

Result: AI algorithms show potential in enhancing diagnostic accuracy and efficiency for conditions such as caries, periodontal disease, and oral cancer. Implementation challenges include data privacy, limited datasets, regulatory compliance, interpretability, clinical workflow integration, and cost, which are amplified in the diverse Indian landscape due to disparities in healthcare access, digital infrastructure, and linguistic diversity.

Conclusion: Addressing challenges through collaboration between researchers, clinicians, policymakers, and industry is essential to responsibly harnessing AI's transformative potential for more accurate, personalized, and accessible oral healthcare.

Keywords: Artificial intelligence, Machine learning, Oral disease diagnosis, AI in dentistry, Convolutional neural network

INTRODUCTION

Early and accurate diagnosis of oral diseases is paramount for effective treatment planning and improving patient outcomes. Traditional diagnostic methods in dentistry rely heavily on clinicians' visual inspection and analysis of radiographic images. While essential, conventional methods have limitations. Subjectivity, inter-observer variability, and the time-consuming nature of manual image analysis can lead to diagnostic errors, delays, or inconsistencies.[1] The need for more objective, accurate, and efficient diagnostic tools has driven the exploration of artificial intelligence (AI) and machine learning (ML) in the field of oral healthcare.

This review aims to comprehensively examine AI and ML applications in oral disease diagnosis, focusing on algorithms, applications, and their challenges.

MATERIAL AND METHODS

An electronic search was conducted using the PubMed database, focusing on English-language, peer-reviewed articles up to March 2025, using the keywords "Artificial Intelligence," "Machine Learning," and "Oral Disease Diagnosis," resulting in 15,554, 12,661, and 6,867 items, respectively. Titles and abstracts were screened to identify articles with significant findings and practical implications, while redundant or low-relevance studies were excluded. The final corpus of sources, detailed in Table 1,[1-12] includes 7 review articles chosen to provide a comprehensive overview

Table 1: A list of selected articles included in this review.

Topic	Type of articles	Year	Author	Publication	Keywords
Deep learning	Review	2015	LeCun *et al.*[2]	Nature	Deep learning, neural networks, ML, representation learning, big data
ML in medicine: A practical introduction	Review	2019	Sidey-Gibbons and Sidey-Gibbons[3]	BMC Medical Research Methodology	ML, medicine, introduction, algorithms, practical guide
Caries detection with near-infrared transillumination using deep learning	Research Article	2019	Casalegno *et al.*[4]	Journal of Dental Research	Caries detection, near-infrared transillumination, deep learning, U-Net, segmentation
High-performance medicine: the convergence of human and AI	Review	2019	Topol[5]	Nature Medicine	High-performance medicine, AI, human intelligence, regulatory compliance, cost
AI in dentistry: chances and challenges	Review	2020	Schwendicke *et al.*[1]	Journal of Dental Research	AI, dentistry, challenges, opportunities, clinical implementation
AI in dentistry: It's applications, impact and challenges	Review	2023	Srivastava *et al.*[6]	Asian Journal of Oral Health and Allied Sciences	AI, dentistry, applications, impact, challenges
An interpretable ML framework for a clinical decision support system in dentistry	Research Article	2023	Li *et al.*[7]	NPJ Digital Medicine	Interpretable ML, decision support, dentistry, random forest, explainability
Validation of AI-driven image analysis for tooth detection and segmentation on panoramic radiographs	Research Article	2023	Leite AF *et al.*[8]	Oral Diseases	ViT, AI validation, tooth detection, segmentation, panoramic radiographs
Deep learning aided decision support for oral cancer	Research Article	2023	Ajeet S *et al.*[9]	Scientific Reports	Oral cancer, OPMDs, deep learning, OSCC, clinical photographs, CNN
AI in salivary biomarker discovery and validation for oral diseases	Review	2023	Adeoye J and Su[10]	Oral Diseases	Salivary biomarkers, AI, multi-omics, diagnostics, oral diseases
Comparison of ex vivo periodontal defects with their respective 3D models generated by AI on CBCT images	Research Article	2024	Gerhardt *et al.*[11]	Scientific Reports	Periodontal defects, 3D models, AI, CBCT, Vision Transformers, 3D analysis
Automated diagnosis and classification of temporomandibular joint degenerative joint disease using the YOLOv10 algorithm on cone-beam computed tomography	Research Article	2025	Mao *et al.*[12]	Dentomaxillofacial Radiology	TMJ, degenerative joint disease, YOLOv10, CBCT, automated diagnosis

OPMDs: Oral cancer and potentially malignant disorders, OSCC: Oral squamous cell carcinoma, YOLO: You Only Look Once, CBCT: Cone-beam computed tomography, TMJ: Temporomandibular joint, CNN: Convolutional neural network, AI: Artificial intelligence, ViT: Vision transformer, ML: Machine learning of the field and 24 original research articles to offer specific, technique-supporting evidence for the application of various AI algorithms in oral disease diagnosis. Relevant data from other electronic sources were also incorporated to supplement these findings.

RESULTS

Prologue to discovery

AI's journey has been marked by alternating periods of rapid advancement ("AI Springs") and periods of reduced progress ("AI Winters"). Recent breakthroughs in computing power, the availability of vast datasets, and the development of sophisticated algorithms have fuelled a dramatic resurgence.[6]

Just as Alan Turing's 1950 Turing Test helped win World War II, we now stand at the precipice of the 4th Industrial Revolution, where AI is set to transform healthcare, particularly in dentistry. This contemporary "AI Spring" is driving a fundamental shift, promising to reshape industries and redefine the relationship between humans and machines.[13]

What is ML?

ML is a subset of AI that empowers systems to learn from data and improve their performance on a specific task without being explicitly programmed with rules for every possible scenario. Adding AI, giving it the power to think like the human brain, is what constitutes ML. It allows systems to learn and improve from experience without explicit programming. In essence, the algorithm learns the relationship between input data and the desired output by following a sequence of steps: Input Data → Analyze Data → Find Patterns → Prediction/Decision → Learns from Feedback.[3]

Algorithms in oral disease diagnosis

The application of AI to oral disease diagnosis relies on an elaborate toolkit of ML algorithms. Just as a dentist integrates various pieces of information, a patient's history, clinical observations, and radiographic findings, these algorithms combine different strengths to achieve a comprehensive and accurate diagnosis.

Convolutional neural networks (CNNs)

The function of a CNN can be likened to a 'master detective' meticulously examining every detail of a radiographic image or clinical photograph, searching for subtle clues.[2] Convolutional layers employ learnable filters to extract features from the input data by performing convolution operations. Non-linear activation functions are employed, allowing the model to learn intricate patterns. Pooling layers reduce the size of the feature maps, which helps decrease computational complexity and prevent overfitting by retaining only the most important information. The extracted features are flattened and fed into fully connected layers, where the final classification or regression task is performed [Figure 1].

Support vector machines (SVMs)

SVMs take on the role of a highly efficient "sorter." SVMs are powerful classification algorithms designed to find the optimal boundary.[14] CNN extracts image features, and the SVM classifies them. The performance of SVM, however, is sensitive to parameter selection; thus, other models are often preferred[15,16] [Figure 2].

Random forest algorithms (RFAs)

If CNNs are the "detectives" and SVMs the "sorters," then RFAs are the expert "consultants." They are ensemble learning

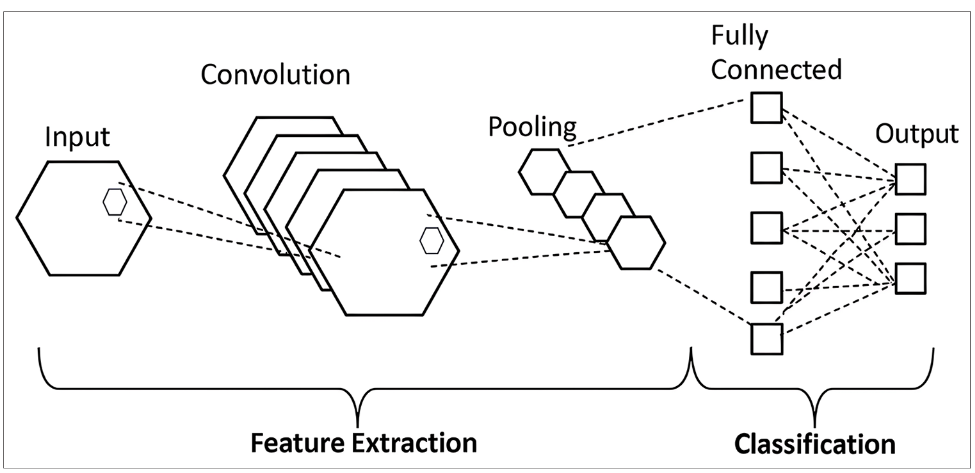

Figure 1: Architecture of a convolutional neural network for Image Classification. [Source: Reference 2]

methods that combine the predictions of multiple decision trees.[17]

A decision tree is a hierarchical structure that splits data based on specific criteria. RFAs improve individual decision trees through bagging and random subspace techniques. Bagging trains each tree on a random data sample, reducing variance, while the random subspace method selects a subset of features to ensure model diversity. The final prediction is an ensemble output, combining all trees for improved accuracy and robustness[7,18] [Figure 3].

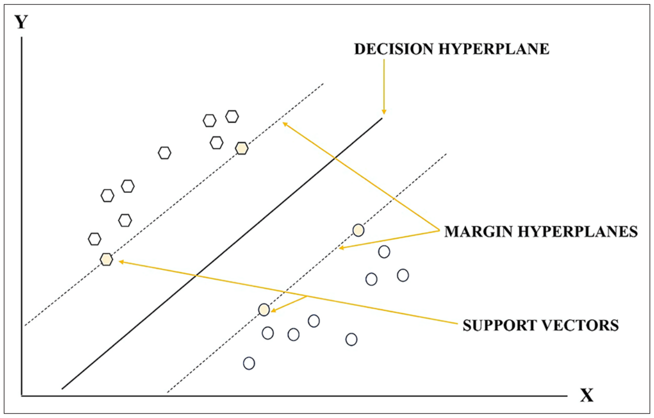

Figure 2: A schematic diagram for support vector machine training. [Source: Reference 3] The X & Y axis are a visual representation of the relation.

Visual transformers (ViTs)

Unlike CNNs, which focus on local patterns, ViTs can capture global relationships.[19] Image patching divides an image into smaller segments, with positional embeddings included to retain spatial relationships. The transformer encoder, using self-attention, assigns importance to patches, while multi-layer perceptrons refine the representations. Finally, the classification head processes the output to make the final prediction[8] [Figure 4].[20]

DISCUSSION

The theoretical capabilities of AI algorithms are translating into tangible benefits in clinical settings, with a growing body of research demonstrating their effectiveness in diagnosing a wide range of oral diseases. These applications span various imaging modalities and data types, highlighting the versatility and adaptability of AI in addressing diverse diagnostic challenges.

Dental caries

CNNs identify subtle radiolucencies indicative of enamel and dentin demineralization, often at earlier stages than are detectable by the unaided human eye.[21] Studies have consistently shown high sensitivity and specificity for CNN-based caries detection, with some systems achieving

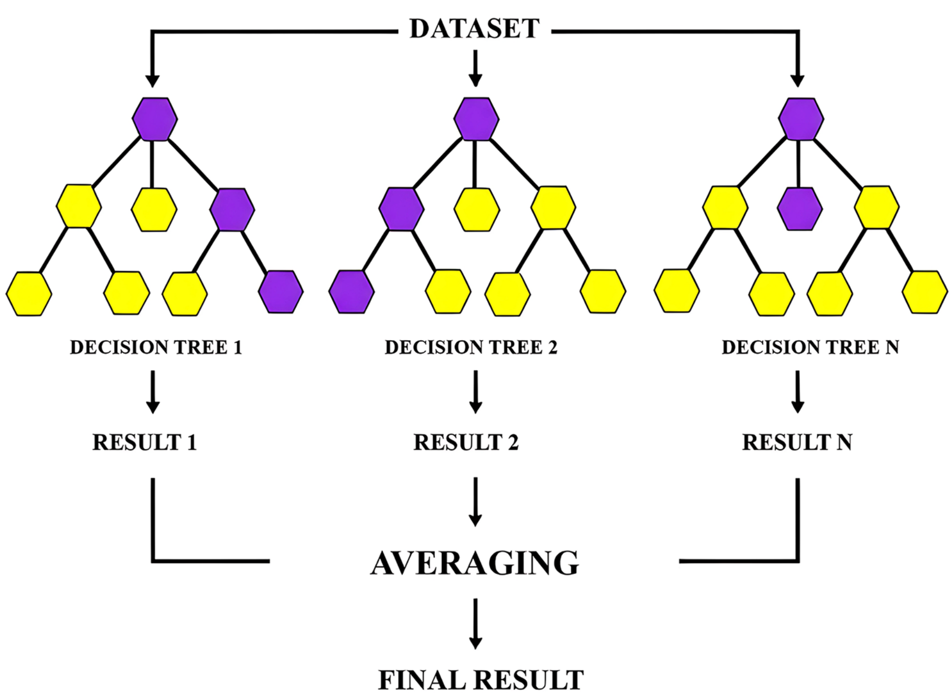

Figure 3: Ensemble learning in random forest: aggregation of decision trees for improved prediction. [Source: Reference 7]

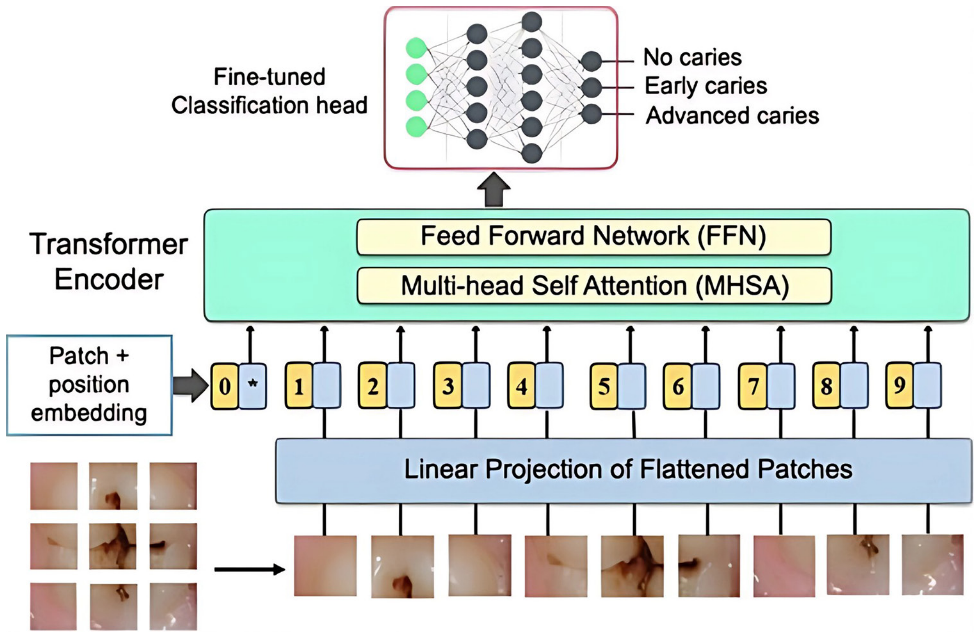

Figure 4: Architecture of the vision transformer for caries classification. [Source: Reference 20]

performance comparable to, or surpassing, that of experienced dentists. Specialized CNN architectures, such as U-Net, have proven particularly effective for segmenting carious lesions, providing precise delineation of the affected area.[4] RFAs have been successfully used to predict caries risk by integrating diverse data sources, including radiographic findings, clinical parameters, patient demographics, and behavioral and dietary factors.[22] Real-time applications, such as "You Only Look Once" (YOLO) family of models, have also demonstrated high precision and recall in detecting interproximal caries, even under complex conditions, including restorations and orthodontic appliances.[23] The integration of AI in caries detection is advancing from simple identification to comprehensive lesion segmentation, classification, and risk assessment, thus supporting more precise and individualized dental care.

Periodontal disease

CNNs have been applied to accurately quantify bone loss, track changes over time, and assist in classifying the stages of periodontitis, achieving a level of accuracy comparable to trained periodontists. RFAs and SVMs have been utilized to analyze clinical parameters, including probing depths, bleeding on probing, and tooth mobility, to assess periodontal disease status and predict its progression.[24] Deep learning models such as YOLOv8 and ResNet18 have achieved up to 97% accuracy in detecting radiographic bone loss and furcation involvement.[25] Vision Transformers have further improved classification tasks, while AI applied to cone beam computed tomography (CBCT) enables 3D analysis of complex defects, aiding in precise and reproducible diagnosis.[11]

Oral cancer and potentially malignant disorders

CNNs have shown promising results in detecting potentially malignant disorders and oral squamous cell carcinoma from clinical photographs of the oral cavity.[9] These algorithms learn to identify subtle visual features associated with malignancy. Beyond clinical photographs, AI is being applied to the analysis of histopathological images of oral tissues, aiding pathologists in identifying cancerous cells and grading tumors.[26]. Furthermore, research is actively exploring the use of AI in conjunction with other imaging modalities, such as autofluorescence and optical coherence tomography, for enhanced oral cancer detection.[27]

Temporomandibular joint (TMJ) Disorders

For TMJ disorders, AI is being increasingly applied to the analysis of CBCT and magnetic resonance imaging (MRI) images of the TMJ, helping to identify structural abnormalities.[12] Deep learning models, such as YOLOv10, have demonstrated high accuracy in detecting TMJ degenerative joint disease features, including erosion, osteophytes, sclerosis, and subchondral cysts, on CBCT.[28] CNNs analyzing MRI have shown 70–99% accuracy in evaluating disc displacement.[29] In addition, RFAs are being explored to analyze TMJ sounds non-invasively, aiding in functional diagnosis through acoustic pattern recognition.[30]

Salivary gland diseases

AI is beginning to be used for image analysis in salivary gland diseases. Furthermore, research is exploring the use of AI for analyzing salivary biomarkers to aid in the diagnosis of conditions such as Sjögren's syndrome and salivary gland tumors.[10] While still developing, AI is shifting diagnostics from image-based morphology to molecular-level analysis. More significantly, AI is decoding complex salivary multi-omics data to uncover hidden biomarker signatures, enhancing diagnostic accuracy.[31]

Challenges in AI implementation

Despite the significant promise and progress of AI in oral disease diagnosis, several critical challenges must be addressed to ensure its successful and responsible implementation. These span technical, ethical, and practical domains:

- Data privacy and security: Compliance with regulations such as HIPAA and GDPR is paramount.[17] These require anonymization, secure storage, and patient consent.[32]
- Limited datasets and data quality: Deep learning relies on large, high-quality, and diverse datasets. In oral health, datasets are often small, poorly labeled, or lack diversity. Class imbalance is a concern.[5]
- Regulatory compliance and validation: AI diagnostic tools are medical devices needing regulatory approval (e.g., Food and Drug Administration), requiring rigorous validation for safety, effectiveness, and utility.[5] Regulatory frameworks are still evolving.
- Interpretability and explainability: Complex deep learning models often operate as "black boxes." Clinicians need transparent decision-making to support clinical judgment.[22]
- Cost and accessibility: High development and implementation costs may limit accessibility.[5]

CONCLUSION

AI is poised to revolutionize oral disease diagnosis, offering a pathway from pixels to improved prognosis. By embracing AI responsibly, addressing ethical and practical concerns, and fostering interdisciplinary symbiosis, we can usher in a new era of more accurate, personalized, and accessible oral healthcare.

As we navigate this transformative period, it is fitting to recall Charles Darwin: "It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change."

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