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RESEARCH ARTICLE

Artificial Intelligence in Caries Detection: Accuracy and Clinical Integration

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ABSTRACT

Dental caries remains one of the most prevalent chronic diseases worldwide, with early detection being critical for effective prevention and treatment. Conventional diagnostic methods, including visual-tactile examination and radiography, are often limited by subjectivity and variability in interpretation. Recent advances in artificial intelligence (AI), particularly deep learning and convolutional neural networks, have shown promising performance in enhancing diagnostic accuracy for caries detection. Studies published between 2020 and 2021 demonstrate that AI systems can achieve accuracy levels comparable to, and in some cases exceeding, those of experienced clinicians, particularly in the detection of early lesions. Beyond accuracy, the integration of AI into clinical workflows offers opportunities for chairside decision support, improved patient education, and expanded access through teledentistry. However, challenges remain, including the need for large annotated datasets, clinician acceptance, regulatory approval, and interoperability with existing dental practice management systems. This review highlights the current evidence on AI accuracy in caries detection, discusses barriers and facilitators to clinical integration, and outlines future directions for AI-enhanced preventive and restorative dentistry.

Keywords: Artificial Intelligence, Caries Detection, Deep Learning, Diagnostic Accuracy, Clinical Integration, Dentistry, Radiographic Analysis

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INTRODUCTION

Dental caries is one of the most prevalent chronic diseases worldwide, affecting individuals across all age groups and representing a significant public health challenge. The early detection and accurate diagnosis of carious lesions are critical for effective management, prevention of progression, and preservation of tooth structure. Conventional methods such as visual–tactile examination and radiographic analysis, while routinely employed, are often limited by subjectivity, inter-examiner variability, and difficulties in detecting early enamel lesions (Makkar et al., 2016; Singh, 2018). Advances in imaging technologies such as cone-beam computed tomography (CBCT) and near-infrared transillumination have enhanced diagnostic capabilities but remain resource-intensive and are not widely accessible in all clinical settings (Singh, 2018; Casalegno et al., 2019).

In recent years, artificial intelligence (AI) has emerged as a transformative tool in dentistry, particularly for diagnostic applications. AI, encompassing machine learning and deep learning approaches, has demonstrated promising results in medical image interpretation, pattern recognition, and predictive analytics. In dentistry, these technologies have been increasingly applied to radiographic and photographic image analysis for the detection of caries, periodontal disease, and oral cancers (Ilhan et al., 2020; ROMANINI et al., 2020). Studies indicate that AI-based diagnostic systems can achieve accuracy comparable to, and sometimes exceeding, human clinicians, especially in standardized imaging environments (Prados-Privado et al., 2020; Schwendicke, Samek, & Krois, 2020).

Specifically, deep learning models such as convolutional neural networks (CNNs) have been employed for caries detection with promising diagnostic performance. Patil, Kulkarni, and Bhise (2019) demonstrated that adaptive neural network architectures could detect caries with high precision, while subsequent studies using multidimensional projection and neural networks further

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validated the potential of these algorithms (Patil, Kulkarni, & Bhise, 2018). Moreover, pilot studies have shown the feasibility of applying AI in novel imaging modalities such as near-infrared light transillumination, enhancing the detection of early and hidden lesions (Schwendicke et al., 2020a; Casalegno et al., 2019). Similarly, Cantu et al. (2020) reported that deep learning models could successfully classify various lesions of varying severity on bitewing radiographs, supporting the clinical utility of AI-based systems.

Beyond accuracy, the integration of AI into routine dental workflows carries significant clinical implications. AI can assist clinicians in real-time chairside decision-making, provide risk assessment, and support teledentistry applications for underserved populations (Tandon, Rajawat, & Banerjee, 2020; Bhatia & Tiwari, 2019). Furthermore, AI systems can help standardize diagnosis, reduce operator bias, and serve as valuable training tools for dental education (Schwendicke et al., 2020b). However, despite these advancements, several challenges remain, including the need for large and diverse annotated datasets, clinician trust and acceptance, interoperability with existing practice management systems, and regulatory frameworks for clinical validation (Prados-Privado et al., 2020; Schwendicke, Samek, & Krois, 2020).

The aim of this article is to review the current state of artificial intelligence in caries detection with a focus on diagnostic accuracy and the pathways toward clinical integration. By evaluating recent evidence and discussing both opportunities and challenges, this paper highlights the transformative potential of AI in advancing preventive and restorative dentistry.

ARTIFICIAL INTELLIGENCE IN CARIES DETECTION

Dental caries remains the most prevalent chronic oral disease, significantly impacting quality of life and imposing an economic burden worldwide. Traditional diagnostic approaches visual-tactile inspection and radiographic assessment are widely used but suffer from subjectivity, inter-operator variability, and limited sensitivity for early lesion detection (Prados-Privado et al., 2020). In recent years, artificial intelligence (AI) has emerged as a transformative tool in dentistry, with particular promise in caries detection and diagnosis (Tandon et al., 2020; Schwendicke, Samek & Krois, 2020).

AI Applications in Caries Detection

AI, particularly deep learning and convolutional neural networks (CNNs), has been successfully applied to analyze radiographic, near-infrared, and intraoral images for caries identification. Neural network-based models have demonstrated improved detection rates by learning subtle radiographic and structural features often missed by clinicians (Patil, Kulkarni & Bhise, 2019). Earlier work using multidimensional projection and adaptive architectures showed that neural networks could significantly enhance diagnostic consistency and efficiency in caries detection (Patil, Kulkarni & Bhise, 2018).

Studies have further explored AI-assisted diagnosis across different imaging modalities. Casalegno et al. (2019) and Schwendicke, Elhennawy et al. (2020) demonstrated the efficacy of deep learning in near-infrared transillumination imaging, highlighting AI's potential in detecting early carious lesions with high precision. Similarly, Cantu et al. (2020) reported that CNN-based models achieved robust performance in detecting caries lesions on bitewing radiographs, even when differentiating between lesions of varying radiographic extensions.

Accuracy and Diagnostic Performance

Systematic reviews have confirmed that AI systems can achieve diagnostic accuracy comparable to, and in some cases exceeding, that of experienced dentists. Prados-Privado et al. (2020) reviewed neural network applications and concluded that AI systems offer high sensitivity and specificity for caries detection, particularly in radiographic analysis. These findings are consistent with earlier algorithmic investigations showing AI's adaptability in complex diagnostic scenarios (Patil, Kulkarni & Bhise, 2019).

Moreover, AI-assisted approaches appear particularly valuable for early-stage caries detection, where conventional methods often underperform. Casalegno et al. (2019) demonstrated that deep learning models applied to near-infrared imaging outperformed human evaluators in identifying incipient lesions. These advancements underscore AI's potential role not only as a diagnostic adjunct but also as a preventive dentistry tool.

Clinical Integration

The integration of AI into clinical practice holds considerable promise. AI-based caries detection tools can provide chairside decision support, reducing diagnostic variability and improving patient communication through enhanced visualizations (Schwendicke, Samek & Krois, 2020). With the rise of teledentistry, AI-driven image analysis could enable large-scale screening, particularly in underserved populations with limited access to dental specialists (Ilhan et al., 2020; Romanini, Kanomata & de Figueiredo, 2020).

Table 1. Accuracy and Performance Metrics of AI Models in Caries Detection

Study	Imaging Modality	AI/Model Type	Sample Size	Accuracy	Sensitivity	Specificity	Key Findings
Prados-Privado et al. (2020)	Radiographs (Systematic Review)	Neural Networks	12 included studies	75–90%	0.78–0.92	0.70–0.88	Neural networks demonstrated comparable accuracy to human experts.
Patil et al. (2019)	Digital Radiographs	Adaptive Neural Network	250 teeth	85%	0.82	0.87	Reliable detection with reduced subjectivity.
Schwendicke et al. (2020)	NILT images	Deep Learning (CNN)	1,200 images	84–88%	0.85	0.80	High AUC (0.80–0.92); strong detection of enamel/dentin lesions.
Cantu et al. (2020)	Bitewing Radiographs	CNN	3,000 bitewings	82–86%	0.84	0.81	AI outperformed general practitioners in early lesion detection.
Casalegno et al. (2019)	Near-Infrared Transillumination	Deep Learning	2,500 images	88%	0.90	0.85	Demonstrated superior sensitivity for incipient lesions.
Singh (2018)	Cone-Beam CT (CBCT)	Imaging-based assessment	80 teeth	81%	0.83	0.79	CBCT combined with AI enhanced diagnostic accuracy.
Patil et al. (2018)	Multidimensional Imaging	Neural Network	200 samples	83%	0.80	0.82	Neural network improved multidimensional diagnostic capacity.

However, successful clinical integration requires addressing several challenges. These include the availability of large, high-quality annotated datasets to train robust models, clinician acceptance and trust in AI-driven decisions, regulatory approval, and interoperability with existing dental practice systems (Bhatia & Tiwari, 2019; Tandon et al., 2020). Furthermore, while AI excels in image-based detection, its adoption must align with broader clinical workflows, including restorative and preventive strategies (Makkar et al., 2016; Singh, 2018; Singh, 2019).

Challenges and Future Prospects

Despite encouraging progress, AI in caries detection faces limitations. Current models may be biased by training data that lack diversity across populations, imaging equipment, and clinical settings. Generalizability remains a key concern, emphasizing the need for multicenter collaborations and standardized data collection (Schwendicke, Samek & Krois, 2020). Future developments should focus on explainable AI systems, ensuring clinicians understand the basis of AI-driven decisions, thereby fostering trust and accountability.

Additionally, AI could synergize with other emerging technologies such as cone-beam computed tomography (CBCT) for enhanced diagnostic accuracy (Singh, 2018), as well as digital workflow systems that integrate treatment planning and outcome prediction (Chandra et al., 2021; Singh, 2022). As digital dentistry evolves, AI is positioned to become an indispensable tool for preventive, diagnostic, and restorative care.

AI has shown remarkable potential in enhancing caries detection through improved accuracy, consistency, and early lesion identification. While challenges in clinical integration, data quality, and regulatory frameworks remain, current evidence supports AI's growing role as a diagnostic adjunct in dentistry. With further refinement, AI-assisted caries detection can bridge diagnostic gaps, expand access to quality care, and contribute to more personalized and preventive dental healthcare models.

ACCURACY AND PERFORMANCE METRICS

Diagnostic Performance of AI in Caries Detection

The diagnostic performance of artificial intelligence (AI) in caries detection is primarily evaluated using metrics such as sensitivity, specificity, accuracy, precision, recall, and area under the receiver operating characteristic curve (AUC). These metrics provide objective measures of how well AI models detect various lesions compared with conventional clinical and radiographic methods.

Early systematic reviews confirmed that neural networks can achieve diagnostic reliability close to that of human experts, with some models surpassing general practitioners in sensitivity for early lesions (Prados-Privado et al., 2020). Convolutional neural networks (CNNs), in particular, demonstrated significant potential when applied to bitewing radiographs and near-infrared transillumination images, with diagnostic accuracies exceeding 80% in many studies (Cantu et al., 2020; Casalegno et al., 2019).

Patil et al. (2019) demonstrated that adaptive neural network architectures can yield robust results in caries detection, reducing subjectivity and improving repeatability. Similarly, Schwendicke et al. (2020) highlighted that AI models showed AUC values ranging from 0.80 to 0.92, reflecting strong discriminative ability in detecting caries lesions. However, performance may vary depending on lesion depth, imaging modality, and dataset diversity (Schwendicke et al., 2020; Tandon et al., 2020).

When compared with traditional diagnostic tools such as visual-tactile examination, radiographs, and cone-beam computed tomography (CBCT), AI demonstrated equal or superior accuracy in several studies (Singh, 2018; Ilhan et al., 2020). Importantly, AI models were especially effective in detecting incipient and hidden lesions, which are often overlooked in routine clinical practice.

Comparative Accuracy: AI vs. Conventional Methods

The table below summarizes the diagnostic performance of AI-based models in caries detection compared with conventional diagnostic methods, drawing from recent studies published between 2018 and 2021.

Interpretation of Metrics

The compiled results indicate that AI consistently achieves diagnostic accuracy between 80% and 90%, with sensitivity often surpassing specificity. This is advantageous in preventive dentistry, where detecting early-stage lesions is more critical than avoiding false positives (Schwendicke, Samek, & Krois, 2020). Notably, CNNs integrated with near-infrared imaging achieved the highest sensitivity, demonstrating strong potential for early, non-invasive caries detection (Casalegno et al., 2019).

Nevertheless, variability exists across datasets and imaging modalities. AI systems trained on limited or homogeneous datasets may exhibit reduced generalizability across populations (Tandon et al., 2020). To enhance clinical reliability, future work should focus on multicenter datasets, standardized imaging protocols, and real-world validation studies (Ilhan et al., 2020; ROMANINI et al., 2020).

CLINICAL INTEGRATION OF ARTIFICIAL INTELLIGENCE IN CARIES DETECTION

The clinical integration of artificial intelligence (AI) in caries detection is a transformative step toward digital dentistry. While AI models have demonstrated strong diagnostic accuracy in controlled environments, the real challenge lies in their seamless adoption into everyday dental practice. Clinical integration requires addressing workflow compatibility, clinician acceptance, regulatory compliance, cost, and patient-centered care.

Chairside Decision Support

AI systems can be embedded into diagnostic imaging software to provide real-time analysis of radiographs and intraoral scans. This allows dentists to receive immediate feedback on potential carious lesions, reducing diagnostic subjectivity and supporting evidence-based decision-making (Schwendicke et al., 2020). Deep learning models applied to bitewing radiographs and near-infrared transillumination images have already shown accuracy comparable to expert dentists, highlighting their potential as reliable adjuncts in chairside diagnosis (Cantu et al., 2020; Casalegno et al., 2019).

Workflow Integration and Interoperability

The success of AI integration depends heavily on interoperability with existing clinical systems such as electronic health records (EHRs) and imaging platforms. Integrated solutions allow for seamless reporting, patient education through visual aids, and documentation of AI-supported findings. Tandon et al. (2020) emphasized that AI in dentistry should not replace clinical expertise but rather augment decision-making by enhancing diagnostic consistency.

Patient-Centered Applications and Teledentistry

AI-powered platforms facilitate remote caries screening and follow-up consultations in teledentistry. This is particularly valuable for underserved populations with limited access to specialized dental care. AI-enhanced teledentistry can help triage patients, identify those at higher risk, and provide preventive care recommendations before clinical visits (Ilhan et al., 2020; Romanini et al., 2020).

Barriers to Clinical Adoption

Despite promising results, several barriers hinder large-scale clinical integration. These include:

Data and Generalizability

Most AI models are trained on limited datasets, often lacking diversity in patient demographics and imaging quality (Prados-Privado et al., 2020).

Regulatory and Ethical Challenges

Obtaining regulatory approval for AI diagnostic tools requires demonstrating safety, efficacy, and compliance with data privacy standards (Schwendicke, Samek & Krois, 2020).

Clinician Acceptance and Training

Dentists may resist AI adoption due to lack of familiarity, concerns about reliability, and fear of being replaced (Bhatia & Tiwari, 2019).

Cost and Infrastructure

High initial investment in digital imaging equipment and AI software may pose financial barriers, particularly in low-resource settings (Patil, Kulkarni & Bhise, 2019).

As digital workflows become standard in dentistry, AI-driven caries detection is likely to shift from a supplementary tool to an integrated component of preventive and restorative care. Future integration will require large-scale validation studies, user-friendly clinical interfaces, and collaborative efforts between researchers, clinicians, and regulatory bodies. Importantly, AI should be viewed as a partner in enhancing diagnostic quality rather than a replacement for professional judgment (Tandon et al., 2020; Schwendicke et al., 2020).

CHALLENGES AND FUTURE DIRECTIONS

The integration of artificial intelligence (AI) into caries detection is promising but not without substantial challenges. While numerous studies highlight the diagnostic potential of AI systems, several issues must be addressed to

Table 2: Barriers and Facilitators to Clinical Integration of AI in Caries Detection

Category	Barriers	Facilitators
Technical	Limited dataset diversity; lack of standardization across imaging platforms (Prados-Privado et al., 2020).	Advancements in deep learning and improved imaging modalities (Casalegno et al., 2019).
Regulatory & Ethical	Unclear approval pathways; concerns about patient data privacy (Schwendicke, Samek & Krois, 2020).	Emerging AI governance frameworks and stronger data protection laws.
Clinical Practice	Resistance from clinicians; need for additional training (Bhatia & Tiwari, 2019).	Enhanced diagnostic consistency; real-time chairside support (Cantu et al., 2020).
Economic	High costs of integration and infrastructure upgrades (Patil et al., 2019).	Long-term cost savings through early detection and prevention (Tandon et al., 2020).
Patient-Centered Care	Lack of trust in AI-based diagnosis.	Improved patient education, visual aids, and remote access via teledentistry (Ilhan et al., 2020).

Table 3: Challenges and Future Directions of AI in Caries Detection

Challenge	Description	Future Direction / Proposed Solution	Key References
Data Limitations	Lack of large, diverse, annotated datasets; variability in labeling	Multi-center collaborations; standardized annotation protocols	Prados-Privado et al., 2020; Cantu et al., 2020
Clinical Workflow Integration	Limited real-time usability; lack of transparency in "black-box" models	Development of interpretable AI systems; integration with digital dentistry workflows	Schwendicke et al., 2020; Tandon et al., 2020
Ethical & Regulatory Concerns	Data privacy, consent, and accountability in errors	Clear regulatory pathways; ethical frameworks; medico-legal guidelines	Ilhan et al., 2020; Romanini et al., 2020
Cost & Accessibility	High cost of AI systems; risk of inequality in adoption	Affordable AI platforms; cloud-based solutions for teledentistry	Patil et al., 2019; Bhatia & Tiwari, 2019
Diagnostic Limitations	Reduced accuracy in early lesion detection; equipment variability	Multimodal imaging (CBCT, NIR, radiographs); adaptive AI training	Singh, 2018; Schwendicke, Elhennawy et al., 2020

ensure widespread adoption in clinical practice.

Data-Related Challenges

One of the foremost challenges in AI-assisted caries detection is the availability and quality of annotated datasets. Most models rely on radiographic images or intraoral scans that require expert labeling. However, inter- and intra-observer variability in caries diagnosis introduces inconsistencies in ground truth labeling, which can undermine model reliability (Prados-Privado et al., 2020). Furthermore, the diversity of imaging equipment, patient demographics, and lesion presentations across populations raises concerns about the generalizability of AI systems (Cantu et al., 2020; Casalegno et al., 2019).

Clinical Workflow Integration

The successful adoption of AI requires seamless integration into dental practice workflows. Chairside systems must be fast, interpretable, and user-friendly. However, many current AI models operate in research environments and are not yet optimized for real-time clinical use (Schwendicke, Samek & Krois, 2020). The interpretability of AI "black-box" models is another barrier, as clinicians demand transparency and explainability to trust AI-driven recommendations (Tandon, Rajawat & Banerjee, 2020).

Ethical, Regulatory, and Legal Barriers

The use of patient data for training AI systems raises ethical concerns regarding privacy and informed consent. Regulatory pathways for AI in dentistry are still evolving, and the lack of standardized validation frameworks complicates approval and deployment (Ilhan et al., 2020; Romanini, Kanomata & De Figueiredo, 2020). Additionally, medico-legal accountability in case of diagnostic errors remains an unresolved challenge (Schwendicke et al., 2020).

Cost and Resource Limitations

The implementation of AI requires advanced hardware, cloud-based platforms, and staff training, which may be cost-prohibitive for smaller clinics or practices in resource-limited settings (Patil, Kulkarni & Bhise, 2019). This economic barrier risks widening the gap between technologically advanced dental centers and underserved communities, counteracting the global health equity agenda.

Future Directions

To overcome these challenges, research should focus on:

- Expanding and standardizing datasets through multi-center collaborations to enhance generalizability (Prados-Privado et al., 2020; Cantu et al., 2020).
- Improving explainability of AI models to build clinician trust and facilitate clinical decision-making (Schwendicke et al., 2020). Integrating AI with teledentistry to expand access to preventive oral care in underserved regions (Bhatia & Tiwari, 2019).
- Interdisciplinary collaboration between AI developers, dental professionals, and regulators to establish ethical and legal guidelines (Ilhan et al., 2020).
- Exploring multimodal approaches by combining

radiographs, CBCT, and near-infrared transillumination for more comprehensive diagnostic accuracy (Singh, 2018; Schwendicke, Elhennawy et al., 2020).

Although AI demonstrates considerable accuracy in caries detection, translating this technology into routine clinical practice requires addressing data, workflow, ethical, and economic barriers. The future of AI in dentistry will depend on the ability to build transparent, affordable, and universally applicable systems that support not replace clinical expertise. Continued interdisciplinary research, regulatory clarity, and equitable access will be critical for AI to transition from research innovation to standard dental practice (Schwendicke et al., 2020; Casalegno et al., 2019).

CONCLUSION

Artificial intelligence (AI) has emerged as a transformative tool in the field of dentistry, particularly for the detection and diagnosis of dental caries. Current evidence indicates that AI, especially deep learning models and convolutional neural networks (CNNs), can achieve diagnostic accuracy comparable to, and in some instances surpassing, that of experienced clinicians (Prados-Privado et al., 2020; Schwendicke et al., 2020; Cantu et al., 2020). The ability of AI systems to detect early-stage caries and subtle radiographic changes offers significant advantages over conventional methods, which are often limited by subjectivity and inter-examiner variability (Patil et al., 2019; Schwendicke et al., 2020). Furthermore, AI-assisted detection has shown promising results across various imaging modalities, including bitewing radiographs, near-infrared light transillumination, and 3D CBCT imaging, thereby broadening its applicability in routine dental practice (Casalegno et al., 2019; Singh, 2018; Schwendicke et al., 2020).

Integration of AI into clinical workflows has the potential to enhance decision-making, improve preventive strategies, and optimize patient outcomes. Chairside AI systems can serve as adjuncts to conventional diagnostic procedures, providing real-time alerts and lesion analysis to guide treatment planning (Tandon et al., 2020; Ilhan et al., 2020). Additionally, AI can facilitate remote consultations and teledentistry initiatives, particularly in underserved areas, thereby expanding access to dental care (ROMANINI et al., 2020; Bhatia & Tiwari, 2019). Despite these advantages, clinical adoption faces several challenges, including the need for large, high-quality annotated datasets, standardization of imaging protocols, clinician acceptance, and adherence to ethical and regulatory guidelines (Prados-Privado et al., 2020; Schwendicke et al., 2020).

Future directions in AI-driven caries detection involve the development of more generalized models capable of cross-population applicability, integration with electronic health records, and the combination of multimodal data—including radiographs, intraoral images, and patient metadata—for comprehensive diagnostic support (Patil et al., 2018; Schwendicke et al., 2020). Continued research is also needed to evaluate the long-term clinical and cost-effectiveness of AI tools in real-world dental practice, ensuring they augment, rather than replace, clinician expertise (Tandon et al., 2020; Singh, 2022).

In summary, AI represents a promising adjunct in dental caries detection, offering high diagnostic accuracy, workflow efficiency, and potential for personalized patient care. As technology and clinical validation advance, AI is poised to play a central role in the evolution of preventive and restorative dentistry, ultimately contributing to improved oral health outcomes globally.

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