Artificial Intelligence in Digital Dentistry: Imaging to Risk Prediction

Abstract

Artificial intelligence (AI) has emerged as a transformative force in digital dentistry, offering significant advancements in diagnostic imaging, risk prediction, and clinical decision support. This review examines the integration of deep learning architectures, particularly convolutional neural networks (CNNs), into dental radiography, cone-beam computed tomography (CBCT), and intraoral scanning workflows. AI-based systems demonstrate diagnostic accuracy comparable to trained clinicians for caries detection, periodontal bone loss assessment, periapical pathology identification, and anatomical landmark detection. Methodological advances including TRIPOD-AI, PROBAST-AI, PRISMA-AI, CLAIM, and the Consensus-Based Checklist for AI in Dentistry frameworks have established standards for transparent reporting and rigorous validation. However, substantial challenges persist regarding data heterogeneity, external validation, algorithmic bias, and clinical workflow integration. The transition from reactive diagnosis to prospective risk stratification represents a paradigm shift requiring longitudinal datasets, calibration analysis, and federated learning approaches. Responsible integration of AI into dental practice necessitates addressing interoperability, clinician literacy, regulatory compliance, and ethical considerations while maintaining human oversight of clinical decision-making. Future directions emphasize harmonization of reporting standards, multi-site validation, and collaborative frameworks between dental professionals and technologists to ensure AI enhances patient care without compromising professional autonomy or ethical principles.

Introduction

Artificial intelligence (AI) has been increasingly integrated into the dental field in the last decade, offering significant advancements in diagnostics, treatment planning, and patient management.[26] In dental imaging, AI holds the potential to transform traditional practices by enhancing diagnostic accuracy, reducing radiation exposure, and improving workflow efficiency.[1,26]

AI serves as an umbrella term encompassing core components including machine learning (ML), artificial neural networks (ANN), and convolutional neural networks (CNN) or deep learning (DL)[22]. These subsets use algorithms to predict outcomes based on provided datasets. Due to the success of AI technology in the medical field and its demonstrated effectiveness, dentistry has increasingly adopted AI for various aspects of improving patient outcomes.[2,25]

AI in Digital Dental Imaging

Clinical Uses in 2D Imaging

AI in digital dental imaging is now most mature in 2D radiography workflows (bitewings, periapicals, panoramics), where deep learning models learn radiographic patterns from labeled datasets and then assist with detection, classification, and measurement tasks[3]. Across recent evidence syntheses, the consistent message is that AI can improve speed and standardization for image-reading tasks, but performance depends heavily on training data quality, labeling rigor, and external validation[3,9]. For caries detection, systematic review evidence reports generally strong diagnostic performance, especially for proximal caries on bitewings[3,5]. AI tends to perform best when the task is narrowly defined and the imaging protocol is consistent[3].

AI is also increasingly used for periodontal imaging support, especially automated measurement of radiographic alveolar bone levels[7,10]. Deep learning approaches

can segment teeth and identify cemento-enamel junction/bone crest landmarks to generate repeatable bone-level estimates[10].

3D Imaging and Implementation

In CBCT, AI is heavily oriented toward segmentation and structure detection (teeth, mandibular canal, sinus boundaries, lesions)[8]. Evidence evaluating AI performance for CBCT segmentation tasks shows strong overall accuracy, supporting AI's role in accelerating digital planning workflows[8].

From an implementation standpoint, AI is moving into routine imaging through commercial, regulated tools that perform detection, segmentation, and triage[8]. Practices still require governance around quality control and documentation of AI usage[8].

Deep Learning and Methodological Advances

The application of deep learning to dental imaging has undergone rapid architectural evolution since approximately 2018[3,6]. Early systems adapted convolutional neural networks originally trained on natural image benchmarks and fine-tuned on small radiographic datasets[3,6].

The transition to detection architectures (Faster R-CNN, YOLO-family models, RetinaNet variants) enabled simultaneous localization and classification[4]. Detection frameworks produce structured outputs that interface more directly with clinical workflows[4]. Semantic and instance segmentation further advanced this trajectory, allowing voxel-precise delineation of teeth and pathology[5,7]. The nnU-Net framework demonstrated that a self-configuring pipeline could match or surpass manually engineered architectures across biomedical segmentation tasks[7].

Domain adaptation, data augmentation, synthetic radiographs, uncertainty quantification, calibration, explainability mapping, and fairness auditing have strengthened methodological rigor[3,6,9]. Federated learning frameworks enable distributed training across institutions without raw data sharing[8]. Systematic

reviews consistently report that internal validation metrics frequently overstate real-world clinical utility when external validation is absent[6,9].

Standards including TRIPOD-AI[11], PROBAST-AI[12], PRISMA-AI[14], CLAIM[16], and the Consensus-Based Checklist for AI in Dentistry[17] have improved transparency and reproducibility.

Artificial Intelligence in Risk Prediction and Clinical Decision Support

AI has expanded beyond image detection toward predictive modelling and risk stratification[15]. Imaging-derived representations can serve as inputs to prognostic models predicting disease progression and treatment outcomes[10]. Periodontal bone level trajectories extracted from serial radiographs have been used to model disease progression rates[10]. This shift from reactive diagnosis to longitudinal patient-level risk prediction requires calibration analysis, fairness auditing, external validation, and longitudinal datasets[11,12].

Integration of AI into Clinical Workflows

AI-Assisted Diagnostics and Workflow Efficiency

Integration of AI into diagnostics helps clinicians interpret imaging results more rapidly and with higher reproducibility, reducing clinician bottlenecks and improving clinical throughput. For example, deep learning systems now enhance radiographic evaluation by highlighting anatomical landmarks and pathological findings.[2]

Automated Clinical Processes

AI platforms can take charge of routine functions;such as capturing structured reports, organizing clinical notes, and extracting key patient data; to free up clinicians for high-value care activities. These automation layers help streamline clinical tasks that would otherwise occupy significant time.[1,8]

Predictive Workflow Optimization

114 Machine learning tools that forecast parameters like treatment duration and patient
115 arrival trends further refine schedule planning. Integrating these predictive insights
116 into appointment systems allows teams to anticipate and manage escalations or
117 delays more effectively, reducing idle time and enhancing patient experience.[8]

118 **Challenges to Clinical Integration**

119 Despite promising gains, practical integration faces hurdles, including
120 interoperability with existing practice management systems, clinician AI literacy,
121 and regulatory considerations. These factors must be addressed systematically to
122 ensure seamless adoption across practices of different sizes.[10]

123 **AI for Patient Management**

124 Extending beyond diagnostics, AI applications such as chatbot scheduling, risk
125 stratification alerts, and automated reminders are improving patient engagement
126 workflows; each of these steps ties back into a broader clinical workflow strategy
127 that prioritizes efficiency and patient care continuity.[15]

128 # Future Directions

129 AI-driven tools enhance diagnostic accuracy, improve efficiency, and elevate
130 patient care[1]. However, AI is not a replacement for dentists' expertise[22]. Dentistry
131 requires clinical judgment, ethical reasoning, and patient-centered care[23,24].

132 Ongoing research, longitudinal validation, and collaborative system design are
133 essential to ensure AI remains unbiased and ethically sound[24]. Responsible
134 integration guided by strong ethical principles and interdisciplinary collaboration
135 will ensure technological advancement prioritizes patient welfare[24].

136 **Abbreviations**
137 **AI** – Artificial Intelligence
138 **ML** – Machine Learning
139 **ANN** – Artificial Neural Network
140 **CNN** – Convolutional Neural Network
141 **DL** – Deep Learning
142 **CBCT** – Cone-Beam Computed Tomography
143 **TRIPOD-AI** – Transparent Reporting of a multivariable prediction model for Individual

144 Prognosis Or Diagnosis for Artificial Intelligence
145 **PROBAST-AI** – Prediction model Risk Of Bias ASsessment Tool for Artificial
146 Intelligence
147 **PRISMA-AI** – Preferred Reporting Items for Systematic Reviews and Meta-Analyses for
148 Artificial Intelligence
149 **CLAIM** – Checklist for Artificial Intelligence in Medical Imaging
150 **nnU-Net** – no-new-Net (self-configuring deep learning segmentation framework)
151 **YOLO** – You Only Look Once (object detection framework)
152 **Faster R-CNN** – Faster Region-based Convolutional Neural Network (object detection)

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