



Artificial Intelligence in Dentistry: Current Applications, Technological Advances, Validation Challenges and Future Directions

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Abstract

Artificial intelligence (AI), encompassing machine learning (ML), deep learning (DL) and related algorithmic approaches, has matured from proof-of-concept demonstrations to clinically promising adjuncts in multiple dental disciplines. Applications include automated radiographic interpretation, caries detection, cephalometric landmarking, implant planning using CBCT, histopathological classification for oral oncology, and workflow automation for prosthodontics and forensic odontology. Although many convolutional neural network (CNN)-based models demonstrate diagnostic performance comparable to experienced clinicians in controlled datasets, translation into routine care is constrained by heterogeneous datasets, insufficient external validation, limited reporting transparency, and unresolved regulatory and ethical issues. This review synthesizes contemporary evidence, maps major application domains, summarizes current validation status, and offers pragmatic recommendations for research and clinical adoption.¹

Keywords: Artificial intelligence; Machine learning; deep learning; convolutional neural networks; dental radiology; implant planning; cephalometrics.

I. Introduction

Advances in computational capacity, algorithmic architectures and the digitization of dental data have catalyzed widespread interest in AI for dentistry. Digital radiographs, cone-beam computed tomography (CBCT), intraoral scanning, electronic dental records and digitized histopathology create rich data sources amenable to ML and DL approaches. AI aims to augment clinician performance by automating repetitive tasks, increasing diagnostic sensitivity, improving treatment planning consistency, and enabling personalized prognostic assessment. Multiple reviews and scoping analyses indicate the majority of dental AI research concentrates on image-based diagnostics—particularly radiology and caries

detection—with expanding activity in implantology, orthodontics and pathology.²

This review (i) summarizes fundamental AI concepts relevant to dental clinicians, (ii) surveys principal clinical application domains with representative high-quality studies, (iii) evaluates validation and external-generalizability challenges, (iv) outlines ethical, regulatory and implementation considerations, and (v) suggests research and translational priorities.

II. Fundamental concepts and terminology

AI is an umbrella that includes ML — algorithms that infer patterns from data — and DL, which uses multi-layered neural networks to learn hierarchical representations. Supervised learning trains models on labeled examples; unsupervised learning seeks latent structure; and reinforcement learning optimizes sequential decisions. Convolutional neural networks (CNNs), a subclass of DL optimized for image data, are the workhorse for radiographic and photographic dental tasks. Transfer learning, data augmentation and ensemble modelling are common practical strategies to address limited dental datasets. For clinicians, understanding performance metrics (sensitivity, specificity, area under the receiver-operator curve [AUC], positive predictive value) and pitfalls like overfitting, class imbalance and spectrum bias is essential before accepting model outputs into practice.³

III. Key application domains

1. Caries detection and conservative dentistry⁴

AI models—especially CNN-based architectures—have been trained to detect radiographic caries on periapical, bitewing and panoramic images. Early influential work demonstrated CNNs with strong diagnostic accuracy on periapical radiographs compared with human readers; subsequent U-Net and segmentation-focused architectures improved lesion localization and assisted clinician interpretation in experimental settings. Systematic reviews report pooled



accuracies that are promising (many studies show AUCs >0.80) but emphasize dataset heterogeneity and label variability by human annotators. Robust multicenter datasets and prospective clinical evaluations remain limited.

2. Dental and maxillofacial radiology (including CBCT)⁵

Automated segmentation, detection of anatomic landmarks and abnormality screening on panoramic radiographs and CBCT have been repeatedly demonstrated. CNNs can segment jaws, delineate mandibular canals and assist in automated report generation; some clinically applicable CBCT systems have been described and externally validated on institutional datasets. However, image acquisition variability (voxel size, field of view, artefacts) and differences in CBCT devices complicate broad generalization; model re-training or domain adaptation strategies are often necessary.

3. Implant planning and surgical workflows⁶

DL approaches applied to 3D CBCT volumes have been developed for automated implant site assessment and surgical guide planning. Representative clinical studies have shown AI-assisted tools can rapidly suggest optimal implant length/diameter, estimate bone dimensions and identify anatomical constraints (e.g., mandibular canal). While these systems can reduce planning time and inter-observer variability, their clinical safety requires prospective validation in multi-center surgical cohorts and human–AI interaction studies.

4. Orthodontics and cephalometrics⁷

AI automates cephalometric landmark detection, measurement extraction, growth prediction and preliminary treatment simulations. Several comparative studies and systematic reviews show that AI-assisted landmarking matches or slightly surpasses human inter-observer reproducibility; nonetheless, edge cases (poorly exposed images, anatomic variants) still require manual oversight. Human–AI collaborative workflows (where AI proposes landmarks and clinicians verify) typically yield the best balance between speed and accuracy.

5. Endodontics⁸

Applications include detection of periapical lesions, root canal morphology segmentation and working length assistance. CNNs applied to radiographs and CBCT can detect pathologies with encouraging sensitivity; however, training datasets are often small and derived from single centers. Reviews stress the need for standardized datasets and

prospective comparisons with clinical outcomes to better estimate diagnostic yield.

6. Periodontology⁹

AI has been used to quantify alveolar bone loss on radiographs, segment periodontal structures and predict disease progression. Reported diagnostic metrics are variable; models trained on intraoral photographs and periapical radiographs show potential for screening and remote monitoring, yet clinical utility depends on integration with periodontal charting, microbiologic and host-response data.

7. Oral pathology and oncology¹⁰

Deep learning applied to photographic images and digitized histopathology slides can classify oral potentially malignant disorders and squamous cell carcinoma with encouraging performance. High-resolution annotated datasets and benchmark challenges have accelerated progress, but the heterogeneity of histology preparation and staining protocols requires rigorous external validation before clinical deployment.

8. Workflow automation, documentation and forensic dentistry

AI can automate tasks such as tooth numbering, restorative status detection, automated chart population and dental record matching for forensics. These applications promise operational efficiency gains in busy practices but must be validated for medico-legal reliability.

IV. Representative high-quality studies (illustrative examples)

- A randomized/controlled performance comparison showed DL systems assisting clinicians in caries detection on bitewing and periapical images, improving sensitivity particularly for early lesions.
- A multicenter study of CBCT-based implant planning using DL algorithms reported accurate bone measurements and feasible automated implant suggestions versus manual planning.
- Scoping and systematic reviews have consistently identified radiology / image diagnostics as the primary focus of dental AI research, noted methodological heterogeneity and called for standardized reporting and prospective clinical trials.

Validation, generalizability and reporting issues



Several methodological weaknesses recur across the literature: small and non-representative datasets, lack of external validation, inconsistent use of ground-truth labels (single vs multiple annotators), absence of prospective clinical testing, and frequent underreporting of data pre-processing and hyperparameter choices. Overfitting is common when models are trained and tested on the same institutional data without rigorous cross-validation. Reporting frameworks and checklists (e.g., TRIPOD-AI, CONSORT-AI when applicable) are increasingly recommended to improve transparency and reproducibility.¹¹

Ethical, legal and regulatory considerations

AI use in clinical dentistry raises important ethical issues: patient consent for secondary use of imaging data; explainability of model outputs; bias in datasets that may disadvantage under-represented populations; accountability for algorithmic errors; and data security. Regulatory pathways for medical AI (e.g., FDA, CE) require evidence of safety and effectiveness; few dental AI tools have received

formal regulatory clearance to date, so clinicians should evaluate vendor claims critically and demand peer-reviewed evidence.¹²

Implementation strategies and best practices for clinicians

1. **Adopt a human-in-the-loop model.** Let AI assist but retain clinician verification. Studies show hybrid workflows yield the best diagnostic performance.
2. **Demand external validation.** Prefer tools validated on multi-institutional datasets different from the training data.
3. **Understand limitations.** Know the model's intended use, population and imaging parameters for which it was trained.
4. **Integrate with workflow.** Plan for interoperability with practice management systems and DICOM/IOT devices.
5. **Data governance.** Ensure secure storage, de-identification of training datasets and compliant consent processes.

Tables

Table 1. Summary of principal AI applications in dentistry (concise)

Domain	Typical data input	Example tasks	Current maturity
Caries detection	Bitewing/periapical images	Lesion detection, segmentation	Early clinical-validation; several experimental tools.
Dental radiology / CBCT	Panoramic & CBCT volumes	Segmentation, canal & landmark detection	Active development; device variability limits generalizability.
Implant planning	CBCT + clinical metadata	Site assessment, guide planning	Prototype/early clinical use; needs prospective surgical validation.
Orthodontics	Cephalograms, intraoral scans	Landmarking, treatment simulation	High accuracy for landmarking; clinical review recommended.
Endodontics	Periapical radiographs, CBCT	Lesion detection, canal morphology	Encouraging results; require larger validation cohorts.
Periodontology	Intraoral photos, radiographs	Bone loss quantification, progression prediction	Emerging; multimodal integration needed.
Oral pathology	Histopath slides, photos	Tumor detection, classification	High potential; needs standardized slide datasets.
Workflow/forensics	Panoramic, dental records	Tooth numbering, record matching	Operational pilots exist; medico-legal reliability pending.

Table 2. Advantages vs Limitations of AI in dentistry

Advantages	Limitations / Risks
Improves diagnostic sensitivity in controlled studies	Dataset bias, limited external validity
Reduces repetitive workload and speeds planning	Overfitting and lack of transparency
Standardises measurements (e.g., cephalometrics)	Regulatory approval and medico-legal clarity lacking
Enables predictive modelling for prognosis	Data privacy and consent challenges



Advantages	Limitations / Risks
Potential for teledentistry and screening	Clinical impact and cost-effectiveness largely unquantified

V. Discussion: Where the field stands and what's needed

The preponderance of evidence confirms that AI can perform many image-based diagnostic tasks at or near clinician performance in controlled conditions. Yet the journey from lab to clinic remains incomplete. To safely harness AI's potential, the dental research community should prioritize the following:¹³

1. **Large, multi-centric, well-annotated datasets** with standardized imaging protocols and detailed metadata. Public benchmark datasets (with appropriate governance) would accelerate robust comparisons.
2. **Prospective clinical studies** that evaluate AI impact on diagnostic decision-making, treatment selection, patient outcomes and cost-effectiveness.
3. **Transparent reporting and reproducibility:** adherence to checklists (TRIPOD-AI, CLAIM for imaging studies) and open sharing of code/models where possible.
4. **Regulatory and ethical frameworks** that address consent, liability and equity — including bias audits and post-market surveillance for deployed systems.
5. **Education of clinicians** on AI fundamentals so they can critically appraise tools, interact with outputs and protect patients.

If these actions are pursued, AI will more likely be integrated as a reliable adjunct to clinical reasoning rather than a niche research curiosity.

VI. Conclusion

AI has demonstrable capabilities that can augment dental practice across multiple domains, especially image-based diagnostics. While promising, current models generally reflect research-stage maturity, requiring rigorous external validation, prospective clinical trials, and regulatory oversight prior to broad clinical deployment. Clinicians and institutions should prioritize human-in-the-loop implementations, demand transparent evidence, and collaborate across disciplines to create trustworthy, generalizable AI solutions that measurably improve patient care.¹⁴

Conflicts of interest

The authors declare no conflicts of interest relevant to this manuscript.

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