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Accuracy of artificial Intelligence in implant dentistry: A review

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Abstract
The integration of Artificial Intelligence (AI) into implant dentistry represents a significant advancement in diagnostic, planning, and surgical procedures. This review aims to evaluate the accuracy of AI-based systems in various aspects of implant dentistry, including diagnosis, treatment planning, implant placement, and post-operative evaluation. AI models, particularly those utilizing machine learning and deep learning algorithms have demonstrated high levels of precision and reliability when interpreting radiographic images such as CBCT, panoramic radiographs, and intraoral scans. Various performance metrics including accuracy, sensitivity, specificity, and area under the curve (AUC) are employed to validate AI tools against human expert benchmarks. Studies report AI accuracy rates comparable to or even surpassing experienced clinicians in identifying anatomical landmarks, detecting pathologies, and planning implant positions. However, factors such as dataset quality, model architecture, and external validation significantly influence these outcomes. Despite promising results, challenges remain regarding generalizability, clinical integration, and ethical considerations. Continuous validation and standardization are essential for the safe and effective deployment of AI in implant dentistry.

Keywords: Artificial intelligence, implant dentistry, accuracy, machine learning, deep learning, CBCT, dental implants, diagnostic imaging, AI validation, clinical decision support systems

Introduction

Dental implantology is a cornerstone of modern prosthodontics providing high success rates for edentulous and partially edentulous patients. However, challenges remain in achieving diagnostic accuracy, effective treatment planning, and consistent postoperative monitoring. Traditional methods often lack objectivity, reproducibility, and time efficiency, which can compromise clinical outcomes [1].

Artificial Intelligence (AI) including machine learning (ML), deep learning (DL), and convolutional neural networks (CNNs) has emerged as a transformative tool in implant dentistry [2, 3]. AI systems trained on extensive datasets can detect anatomical structures, assess bone quality, predict surgical outcomes, and identify implant systems with remarkable speed and accuracy. This data driven approach enhances precision and consistency, reducing human error and variability [4]. AI's ability to analyze complex imaging data such as cone-beam computed tomography (CBCT), panoramic, and periapical radiographs allows for automated, objective decision making in diagnosis and treatment planning [5]. These systems also support prosthetic rehabilitation and postoperative monitoring contributing to improved clinical workflows and outcomes [6].

This review provides a comprehensive overview of the accuracy and current applications of AI in implant dentistry, highlighting its role in diagnostics, planning, and follow-up. It also discusses existing limitations, including issues with data quality, algorithm transparency, ethical concerns, and the need for clinical validation. By synthesizing recent literature, this study explores AI's growing impact and future directions in the field.

Fundamentals of artificial intelligence in dentistry

Artificial Intelligence (AI) in dentistry is a transformative digital tool that simulates human cognitive processes such as reasoning, learning, and problem solving using machines.

Richard Bellman (1978) defined AI as "the automation of activities that we associate with human thinking such as decision making, problem-solving, and learning [7]. In dental practice, AI assists in diagnostics, treatment planning, patient monitoring, and outcome prediction by recognizing patterns in complex data sets. It is especially valuable in radiology, prosthodontics, orthodontics, and implantology for enhancing accuracy, consistency, and efficiency [8-11].

AI operates through core functions: knowledge representation (data organization), learning (adapting with experience), reasoning (logical inference), perception and action (interpreting data through sensors). Machine Learning (ML), a key AI subset, enables systems to learn from annotated data like radiographs and Electronic Health Records (EHRs) to predict outcomes such as caries progression or implant failure. ML models can be supervised, unsupervised, semi-supervised, or reinforcement based [10, 11]. Deep Learning (DL), an advanced ML approach, uses deep neural networks (DNNs) to extract complex features from large datasets like CBCT scans and panoramic images [4, 11, 12]. Among DL architectures, Artificial Neural Networks (ANNs) and Convolutional Neural Networks (CNNs) are widely used in dentistry. ANNs are effective for classification tasks, while CNNs specialize in image based diagnostics, including caries detection, implant identification, and anatomical segmentation. CNNs have achieved diagnostic accuracies above 90% in identifying dental implant systems [8, 13].

The effectiveness of AI systems in dentistry is highly dependent on data quality and diversity. Key data sources include:

- CBCT scans, providing 3D images for implant planning and bone evaluation [9, 14].
- Panoramic radiographs, aiding in general diagnostics[10,11]
- Intraoral scans (IOS), enabling detailed digital impressions and occlusal analysis [14].
- Electronic Health Records (EHRs), offering demographic and clinical data for personalized risk prediction [10].
- Periapical and bitewing radiographs, useful for detecting subtle bone and periodontal changes [11].
- 3D facial scanners, facilitating esthetic and prosthetic planning by integrating facial and intraoral data [14].

The integration of these diverse data streams through AI supports a shift toward personalized, minimally invasive, and highly accurate dental care.

Applications of artificial intelligence in implant dentistry

The integration of Artificial Intelligence (AI) in implant dentistry has transformed diagnostic, planning, surgical, and rehabilitative phases. AI improves workflow efficiency, precision, and predictability by minimizing human error and supporting clinical decision making through data driven algorithms.

AI-powered diagnostic imaging has become foundational. Using machine learning (ML) and deep learning (DL), particularly convolutional neural networks (CNNs), AI interprets complex radiographs like panoramic images and cone-beam computed tomography (CBCT) scans with high accuracy. These models detect anatomical landmarks, apical lesions, cysts, sinus boundaries, and nerve locations critical for implant placement [7, 8, 11]. CNNs have demonstrated over 90% accuracy in identifying implant models from radiographs [8]. AI also assists in segmenting and classifying CBCT tissue types, automating bone and soft tissue analysis and improving diagnostic consistency [14].

AI-integrated planning software uses digital impressions and CBCT to recommend implant locations, depths, and angulations. These models generate precise surgical guides that enhance accuracy and reduce surgical risk [9, 14]. Virtual patient modeling combines facial scans, intraoral scans, and radiographs to produce detailed 3D plans. Platforms like coDiagnostiX® use AI for safe implant trajectory planning, risk assessment, and prosthetic driven positioning promoting minimally invasive surgery even in complex full arch cases [14].

Bone quality and quantity are essential to implant success. Traditionally assessed subjectively, they can now be evaluated objectively using AI. DL models trained on annotated CBCT and panoramic images analyze grayscale intensity to assess bone density, cortical thickness, and trabecular patterns, correlating well with clinical evaluations [9, 14]. This facilitates improved pre-surgical assessment and planning.

AI also assists in selecting the ideal implant type, size, and surface based on anatomical, biomechanical, and esthetic considerations. Models factor in bone condition, occlusal load, and esthetic zones to recommend suitable implant systems [9, 11]. Advanced platforms incorporate factors like nerve proximity and tooth root positioning to optimize placement. Some systems are integrated with robotic surgery tools, allowing millimeter level precision during implant placement, reducing complications like sinus perforation or nerve damage.

In prosthetic rehabilitation, AI combines intraoral scans, facial data, and jaw motion tracking to automate crown, bridge, or full-arch prosthesis design. AI-based CAD/CAM software enhances morphology, occlusion, and esthetics tailored to each patient [11]. It can also suggest abutment types and materials based on biomechanical load and esthetic needs, resulting in fewer adjustments and more successful outcomes [15].

Postoperative monitoring is enhanced by AI systems capable of detecting early signs of complications like peri-implantitis, bone loss, or prosthesis loosening. AI can track radiographic changes over time to identify inflammation or bone resorption [7, 10]. Emerging biosensor technology integrated with AI platforms can monitor parameters like pH, pressure, and temperature in real time. Additionally, AI analyzes behavioral data such as smoking and oral hygiene habits to predict implant failure risks and generate personalized care plans [11, 16].

Evaluation of accuracy in ai systems

Assessing the accuracy of Artificial Intelligence (AI) systems in implant dentistry is critical to ensure their reliability, clinical applicability, and patient safety. AI models must not only perform with precision but also align with the clinical standards traditionally upheld by human experts. Various metrics, comparative studies, validation benchmarks, and influencing factors contribute to determining the true clinical value of AI applications. Several standardized metrics are used to evaluate the diagnostic and predictive performance of AI systems in dentistry:

- **Accuracy:** Proportion of correctly predicted outcomes (true positives + true negatives) among all cases analyzed.
- **Sensitivity (Recall):** The ability of the AI model to correctly identify positive cases (e.g., identifying a bone lesion or peri-implantitis).
- **Specificity:** The model's capacity to correctly identify

negative cases (e.g., recognizing healthy bone or absence of complications).

- **Precision:** Proportion of true positive predictions among all positive predictions made by the model.
- **F- Measure:** Harmonic mean of precision and recall; particularly valuable when data are imbalanced.
- **Area under the Receiver Operating Characteristic Curve (AUC-ROC):** Reflects the model's ability to discriminate between classes across various thresholds. AUC values closer to 1 indicate excellent model performance [4, 10].

These metrics are essential in classification of problems, such as determining whether an implant site is suitable or if a radiograph reveals pathology. A study by Hadj Saïd *et al.* reported a deep learning model achieving a diagnostic accuracy of 93.8%, sensitivity of 93.5%, specificity of 94.2%, and AUCs exceeding 0.91 for various implant systems, demonstrating its high reliability in radiographic classification.[8] AI systems are increasingly compared with expert human clinicians to determine parity or superiority. In many diagnostic tasks such as detecting caries, apical lesions, or classifying implant types AI models have shown performance equal to or better than dental professionals, particularly in terms of consistency and speed.

Unlike human clinicians, whose diagnostic accuracy may vary based on fatigue, training level, and subjective bias, AI maintains consistent performance once trained on quality datasets [10, 11]. However, current consensus emphasizes that AI should act as a decision support tool, not a replacement, especially for complex cases requiring clinical judgment, empathy, and ethical considerations. AI outperforms novice clinicians in pattern recognition tasks involving radiographs but still relies on experienced clinicians for interpretive context and decision making when data ambiguity exists [10].

Validation is essential to evaluate the generalizability of AI systems across populations, clinical settings, and devices [17].

Most models are validated using: Hold-out test sets, Cross-validation (k-fold), External datasets.

In dentistry, the lack of large, annotated, and diverse datasets presents a challenge for external validation. Nonetheless, recent studies have demonstrated strong performance: Hadj Saïd *et al.* trained a CNN using over 1,200 radiographic images of dental implants and achieved consistently high performance metrics across test datasets [8]. Panahi and Azarfardin reviewed AI applications in implant planning and confirmed that models trained on diverse CBCT data could predict bone density and implant positioning with strong validation results [9]. Afrashtehfar *et al.* emphasized the importance of benchmarking AI tools (like coDiagnostiX®) against standard planning systems, validating their superiority in planning accuracy and workflow efficiency [14]. Transparent benchmarking using public datasets and peer-reviewed validation protocols remains a major priority for future clinical AI systems.

Multiple factors influence the overall accuracy of AI models in implant dentistry

- **Data Quality:** High-resolution, artifact free images (e.g., CBCT or panoramic radiographs) significantly improve training outcomes. Poor quality data with noise, motion artifacts, or missing annotations can drastically reduce model reliability [9, 14].
- **Model Architecture:** Advanced architectures such as deep convolutional neural networks (CNNs) and multimodal fusion models outperform traditional machine learning algorithms due to their ability to learn complex patterns across data types [4, 11].
- **Training Size and Diversity:** Larger datasets allow models to generalize across different patient anatomies, scanner brands, and clinical conditions. AI trained on small, homogeneous datasets risks overfitting and may not perform well on unseen cases [4, 10].
- **Annotation Consistency:** Expert labeled datasets are essential. Inconsistent or subjective labels during training may introduce bias into the model.
- **Bias and Overfitting:** Bias in data selection (e.g., single center data) or demographic underrepresentation can reduce fairness and reliability. Cross-validation and external testing are required to minimize such risks [4, 10].

Artificial Intelligence (AI) is redefining the clinical decision-making landscape in implant dentistry by providing real time, evidence based support across the continuum of care. From treatment planning to risk evaluation and postoperative management, AI offers tools that enhance accuracy, efficiency and individualization of treatment strategies. By integrating vast datasets from imaging, patient histories, and clinical outcomes, AI systems can assist clinicians in making more informed, data-driven decisions [18].

AI's most impactful application lies in supporting clinicians during the diagnostic and planning phases. AI-driven systems can synthesize data from CBCT scans, panoramic images, intraoral scans, and electronic health records (EHRs) to create optimized treatment plans tailored to individual anatomical and clinical conditions [11, 14]. AI platforms such as coDiagnostiX® and similar digital planning tools automate multiple aspects of implant planning: Identifying optimal implant angulation and depth, Avoiding anatomical risks like inferior alveolar nerve or sinus involvement and Simulating prosthetic restorations in occlusion for a restoration-driven approach [14].

These systems often employ convolutional neural networks (CNNs**)** to extract and analyze anatomical structures, enabling comprehensive 3D visualizations and reducing planning time. Additionally, AI-integrated CAD/CAM software aids in designing personalized prostheses, selecting abutments, and aligning esthetics with function [11, 13].

In advanced cases, AI even suggests implant sizes, surface types, or surgical approaches based on the complexity of the case and the patient's medical history. This data driven support allows clinicians to evaluate multiple scenarios and select the most predictable one with enhanced precision. AI models trained on large clinical datasets can predict adverse outcomes such as peri-implantitis, marginal bone loss, and implant failure. These risk prediction algorithms consider factors including: Smoking status, Systemic diseases (e.g., diabetes), Bone quality and volume, Periodontal status, Oral hygiene habits, Prosthetic design and occlusion.

By analyzing these parameters, machine learning (ML) models identify patterns and provide personalized risk scores, alerting clinicians to high-risk cases before implant placement. Such tools enhance preventative strategies and may guide clinicians to adopt alternative surgical protocols (e.g., staged surgeries or bone augmentation) or stricter follow-up regimens [4, 9, 11]. Panahi and Azarfardin discussed AI-based modeling that uses CBCT data to predict bone quality and identify patients at risk for compromised implant osseointegration [19]. Similarly, Rokaya *et al.* highlight AI's ability to identify complications like periodontal bone loss and root fractures from periapical radiographs using image classification techniques [11].

AI is also showing promise in predictive maintenance, where periodic image inputs help detect subtle radiographic changes indicative of future complications much before they are clinically evident. Several published studies demonstrate AI's effectiveness in real world dental implant scenarios:

- **Implant Identification via Radiographs:** Hadj Saïd *et al*. developed a CNN model that correctly identified implant brand and model from radiographs with 93.8% accuracy. This tool is valuable when patients lack implant documentation or in medico-legal and forensic situations [8].
- **Bone Quality Assessment:** Afrashtehfar *et al*. discussed the use of AI models for predicting bone density using panoramic radiographs, which correlated well with tactile assessments by implant surgeons. These findings support the reliability of AI in assisting treatment planning even in settings where CBCT is unavailable [14].
- **Computer-Aided Implant Planning (CAIP):** Panahi and Azarfardin reported how AI-driven CAIP systems automatically analyzed CBCT data, identified anatomical landmarks, and proposed safe implant sites. The accuracy of these systems matched or exceeded that of manual planning, particularly in complex anatomical cases [9].
- **Predictive Modeling for Peri-Implantitis:** Rokaya *et al*. emphasized AI's role in predicting peri-implant bone loss by analyzing radiographic patterns in conjunction with patient risk factors. The algorithm accurately forecasted bone loss progression, enabling timely intervention [11].

These case studies affirm AI's capability to enhance diagnostic accuracy, optimize planning decisions, and improve long-term treatment success.

Challenges and limitations of ai in implant dentistry

Despite its transformative potential, the integration of Artificial Intelligence (AI) into implant dentistry faces numerous challenges across technical, ethical, legal, and practical domains [18]. Understanding these limitations is crucial to ensure safe, equitable, and effective clinical implementation.

A primary challenge is the need for high-quality, diverse datasets to train accurate and reliable AI models. Dental imaging data such as CBCT and panoramic radiographs often suffer from inconsistencies due to noise, motion artifacts, and variability in imaging protocols across different clinics or devices [9, 14]. Dataset bias is another concern, particularly when data is limited to specific populations or anatomical types. As Ghaffari *et al*. emphasized, such homogeneity increases the risk of overfitting, reducing model generalizability in real world scenarios [4]. In addition, manual annotation errors during dataset preparation can further impair model accuracy, particularly in segmentation or peri-implant disease detection tasks.

A significant limitation of many AI systems, particularly deep neural networks, is their "black-box" nature. While these models offer high diagnostic performance, their decision making processes lack transparency, making it difficult for clinicians to interpret or validate outcomes [4, 10]. Farhana Pethani noted that this lack of explainability may hinder clinician trust and adoption, especially in cases involving medico-legal responsibility or regulatory decision-making [10]. Although Explainable AI (XAI) is being developed to improve interpretability, its use in dental applications is still emerging [18].

Ethical and legal issues also present major barriers. Key concerns include patient data privacy, consent for using EHRs or radiographs in training datasets, algorithmic bias potentially disadvantaging minority groups, and ambiguity over accountability for AI-driven outcomes [18, 20]. Rokaya *et al*. and Ghaffari *et al*. emphasized the need for strong governance frameworks, secure data handling protocols, and ethically sound model development [4, 11]. Non-compliance with data protection laws like GDPR or HIPAA could result in legal penalties and diminished patient trust. Moreover, cross border data use for AI training raises concerns over data ownership and sovereignty.

Clinically, one of the largest barriers is integrating AI tools into existing workflows. Many systems are standalone and incompatible with current dental software, disrupting standard processes and increasing chairside time. Their effective use often requires advanced digital infrastructure and clinician training, which can be resource intensive [9, 11]. Afrashtehfar *et al*. observed that even with accurate tools like coDiagnostiX®, successful implementation depends heavily on the operator's technical skills and the availability of integrated digital systems [14]. Without interoperability standards, embedding AI into EHR or radiology platforms remains difficult, limiting real-world application.

Regulatory challenges further impede clinical adoption. Most dental AI systems remain unapproved by key regulatory bodies like the Food and Drug Administration (FDA) or European Commision (CE), making their use largely experimental [10]. Pethani noted that although some medical AI tools have received regulatory clearance (e.g., for diabetic retinopathy), no AI systems in implant dentistry have achieved similar approval [10]. This regulatory gap creates risks related to product reliability, exaggerated claims, and patient safety. The development of clear validation protocols, standardized clinical trials, and ongoing post market surveillance is essential. Additionally, the standardization of performance metrics, labelling conventions, and reporting formats is urgently needed to enable fair benchmarking and comparative evaluation of AI tools [4].

Future prospects and research directions

The application of Artificial Intelligence (AI) in implant dentistry is rapidly advancing, with future developments poised to overcome current limitations in interpretability, generalizability, and personalization. Emerging technologies such as federated learning, real time AI assisted robotics, explainable AI (XAI), and personalized treatment planning are expected to revolutionize the field, making dental implantology more data secure, patient centered, and clinically robust [21].

Federated learning is an innovative training approach that enables multiple institutions to collaboratively train AI models on decentralized datasets without sharing raw patient data. This method addresses critical concerns around privacy and allows large scale, multicenter model development using diverse data from CBCT, panoramic radiographs, and clinical records [18, 19]. Ghaffari *et al*. noted that such distributed learning strategies enhance model robustness across ethnicities, anatomical variations, and global populations while promoting equitable, unbiased AI adoption in clinical settings [4].

In parallel, AI is becoming integral to robotic assisted implant surgeries, enhancing precision and safety. AI integrated robots can translate preoperative plans into millimeter accurate movements, adapt to real time anatomical changes, and provide surgeons with visual and haptic feedback [9, 14]. As Panahi and Azarfardin described, real time CBCT data processed through deep learning models can guide surgical arms, minimizing deviation and reducing the risk of nerve or sinus injury [9]. These advancements also shorten procedure time and improve implant longevity. AI-powered navigation systems are being developed to track surgical instruments, visualize critical anatomy, and deliver real time alerts particularly useful in complex procedures like full arch or zygomatic implant placement.

A major limitation of current AI systems is their "black-box" nature producing results without transparent reasoning. Explainable AI (XAI) addresses this by offering interpretable models that clarify how decisions are made, which data features were most influential, and the confidence level of predictions [4, 10]. As Farhana Pethani emphasized, clinical trust and accountability rely on transparency, especially in dentistry, where variability in patient anatomy and treatment plans is high [10]. XAI approaches, such as visual saliency maps or decision trees, support clinicians in evaluating AI recommendations and pave the way for regulatory approvals and ethical clinical use.

Personalized implant treatment planning represents another frontier in AI application. AI can integrate multimodal data including CBCT derived bone morphology, patient medical history, behavioral factors (e.g., smoking), periodontal and occlusal status, and esthetic preferences to deliver tailored treatment protocols [9, 11, 14]. These systems can recommend specific implant dimensions, surface properties, abutment types, and prosthetic materials, along with success probabilities and predicted risks. Afrashtehfar *et al*. and Rokaya *et al*. envision AI systems providing holistic patient profiles to guide clinicians from diagnosis through long term maintenance [11, 14]. In the future, digital twins virtual replicas of patients may enable simulation and testing of various implant protocols before clinical execution, optimizing safety and outcomes through predictive modeling.

Conclusion

Artificial Intelligence (AI) is revolutionizing implant dentistry by enhancing diagnostic imaging, virtual planning, bone assessment, surgical guidance, prosthetic design, and postoperative monitoring. Powered by machine learning (ML), deep learning (DL), and convolutional neural networks (CNNs), AI systems have demonstrated high accuracy in tasks such as implant identification and bone quality evaluation, often rivaling human clinicians [8, 11, 14]. AI supports clinical decision making by offering personalized treatment recommendations, predicting risks like peri-implantitis, and streamlining workflows through integration of CBCT, intraoral scans, and EHRs [4, 9, 11]. Benefits include improved diagnostic precision, minimally invasive procedures, tailored care, and enhanced efficiency. However, limitations such as data quality, lack of transparency, clinical usability, and regulatory concerns must be addressed [4, 10].

The future of AI in implant dentistry includes federated learning for secure data sharing, real time robotic-assisted surgery, and explainable AI (XAI) to improve clinician trust [4, 9, 14]. As technologies advance and regulatory standards evolve, AI is expected to become a key clinical partner augmenting expertise, improving predictability, and delivering personalized, safe, and effective implant care.

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Not available.

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