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ARTIFICIAL INTELLIGENCE IN DENTAL IMPLANTOLOGY: A SYSTEMATIC REVIEW OF CURRENT APPLICATIONS, PERFORMANCE, AND CHALLENGES

[1]Dr. Annem Venkata Shalmeeja, [2]*Dr. Divya Kadali, [3]Dr Farouq Afsha Md, [4]Dr. Reehana Pathan and [5]Dr. Lokeswari Devi Donavalli

[1]MDS 1st Year, Department of Periodontics and Implantology, DRS. Sudha and Nageshwar Rao Siddartha Institute of Dental Sciences, Chinaoutapalli, Andhra Pradesh, India.
[2]Associate Professor, Department of Periodontics, Care Dental College and Hospital, Guntur. Andhra Pradesh, India.
[3]Senior Lecturer, Department of Oral and Maxillofacial Surgery, Care dental college and hospital, Guntur.
[4]BDS Clinical Practitioner, Care Dental College, Guntur, Andhra Pradesh.
[5]MDS 1ST Year, Conservative and Endodontic Department, Gitam Dental College, Visakhapatnam, Andhra Pradesh, India.

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***Corresponding Author**
Dr. Divya Kadali
Associate Professor, Department of Periodontics, Care Dental College and Hospital, Guntur. Andhra Pradesh, India.

ABSTRACT

Objective: This systematic review evaluates the scope and performance of artificial intelligence (AI) applications in dental implantology, focusing on their roles in implant type recognition, surgical planning, peri-implantitis prediction, and implant design optimization. **Methods:** A comprehensive literature search was conducted across PubMed, Scopus, Web of Science, and Cochrane Library for studies published between January 2020 and March 2024. Eligible studies included original research, clinical trials, and in vitro studies reporting on AI tools in implant dentistry. Data were extracted regarding study design, AI techniques, sample size, diagnostic or predictive accuracy, and outcome measures. Risk of bias was evaluated using the Joanna Briggs Institute (JBI) and Newcastle–Ottawa Scale (NOS) checklists. **Results:** Thirty-six studies met the inclusion criteria. AI models demonstrated promising results: implant type identification accuracies ranged from 89% to 98.5%; implant planning models improved anatomical segmentation and reduced diagnostic time; peri-implantitis prediction tools achieved up to 90% accuracy; and AI-assisted finite element analysis optimized implant designs by reducing bone stress by up to 36.6%. However, barriers such as heterogeneity in datasets, lack of external validation, algorithm transparency, and ethical concerns were noted. **Conclusions:** AI applications in implant dentistry exhibit strong potential across diagnosis, planning, prognosis, and design. However, broader clinical validation and implementation frameworks are essential for safe, standardized integration.

1. INTRODUCTION

Dental implantology has witnessed significant advancements over recent decades, particularly in diagnostic imaging and digital treatment planning. The integration of Artificial Intelligence (AI)—which encompasses machine learning (ML), deep learning (DL), and neural networks—has added a new dimension to this transformation. AI offers scalable solutions for pattern recognition, decision-making, prediction modeling, and image processing. In implantology, these capabilities are particularly valuable for handling complex diagnostics, enhancing planning accuracy, and improving patient outcomes.

Given the expanding research on AI's clinical efficacy, this review aims to systematically assess current literature on AI applications in implant dentistry, evaluate performance outcomes, and identify gaps and limitations in its clinical translation.

2. MATERIALS AND METHODS

2.1. Literature Search Strategy

A comprehensive literature search was conducted across PubMed, Scopus, Web of Science, and Cochrane Library databases for English-language publications dated between January 2020 and March 2024. The Boolean search strategy combined keywords and MeSH terms:

- ("Artificial Intelligence" OR "Machine Learning" OR "Deep Learning") AND ("Dental Implants" OR "Implant Planning" OR "Implant Identification" OR "Peri-implantitis" OR "Implant Design")

2.2. Inclusion and Exclusion Criteria

Inclusion Criteria

- Peer-reviewed original studies (clinical, in vitro, or retrospective)
- Use of AI tools for diagnosis, treatment planning, prediction, or design optimization in implant dentistry
- English language

Exclusion Criteria
- Reviews, editorials, letters, and opinion pieces
- Animal studies
- Studies without a direct AI application to implantology

2.3. Study Selection and Data Extraction
Two independent reviewers screened titles and abstracts, followed by full-text reviews. A third reviewer resolved any disagreements. Extracted data included:
- Author and year
- Study type and country
- AI algorithm/model used
- Imaging modality
- Sample size
- Diagnostic/algorithmic performance (accuracy, sensitivity, specificity)

2.4. Quality Assessment
The Joanna Briggs Institute (JBI) checklist was used for quasi-experimental studies, and the Newcastle–Ottawa Scale (NOS) for clinical research. Studies scoring 7 or higher on the NOS were considered high-quality.

3. RESULTS
3.1. Overview of Included Studies
From 207 initially retrieved articles, 36 studies met the inclusion criteria. The majority were retrospective (n=23), while others included clinical trials (n=6), in vitro studies (n=5), and prospective observational designs (n=2).

Table 1: Summary of Included Studies on AI in Dental Implantology.

Author (Year)	Country	AI Model Used	Application Area	Sample Size	Accuracy (%)
Lee et al. (2023)	South Korea	ResNet-50, VGGNet	Implant identification	3000	97.1
Macrì et al. (2024)	Italy	U-Net 3D	Implant planning (CBCT)	150 CBCTs	N/A
Lyakhov et al. (2022)	Russia	CNN	Implant survival prediction	1646	94.5
Park et al. (2023)	Korea	Deep CNN	Implant classification	156,965	98.5
Sukegawa et al. (2023)	Japan	ResNet-152	Implant identification	9767	98.41

3.2. Implant Type Recognition
Seven studies used AI models for identifying dental implant systems using panoramic or periapical radiographs. CNN-based architectures such as VGG-16, YOLO, and GoogleNet demonstrated robust classification accuracies.
Sukegawa et al. applied deep CNNs to 9767 panoramic images, achieving 98.41% accuracy.[5]
Said et al. used GoogLeNet on 1206 radiographs, reaching 93.8% accuracy.[8]
These models enhance efficiency, particularly in cases lacking implant documentation.

3.3. AI in Implant Planning
Ten studies employed AI to automate 3D anatomical segmentation and preoperative assessments. AI tools were trained on CBCT scans to segment mandibular canals, detect sinus cavities, and assess bone dimensions.

U-Net models demonstrated precise segmentation of critical anatomical features.[3]

Macrì et al. reported AI tools were up to 116 times faster than manual planning, significantly reducing clinician workload.[3]

3.4. Prediction of Peri-Implantitis
Five studies evaluated AI models for early detection of peri-implantitis. Algorithms included:
Region-based Convolutional Neural Networks (R-CNN)
Support Vector Machines (SVM)
Random Forest Classifiers
AI tools processed clinical and radiographic data to identify early disease markers and risk factors.
Reported prediction accuracies ranged from 73% to 90%.[13][14]
Logistic regression models were effective in classifying mild to severe inflammation.

3.5. Prognosis and Design Optimization
AI-enhanced Finite Element Analysis (FEA) was featured in four studies focused on implant design. These models predicted bone stress distribution and optimized implant parameters like diameter, length, and porosity.

AI-designed implants showed up to 36.6% reduction in interface stress.[10]

Design simulations allowed for personalized implant geometry selection.

4. DISCUSSION
The integration of AI in dental implantology is steadily transforming various stages of clinical workflow—from diagnosis and planning to prognosis and design optimization. This review highlights several high-performing AI models that have demonstrated clinical potential.

4.1. Implant Identification and Classification
Implant recognition through AI has shown exceptional accuracies, especially with convolutional neural networks (CNNs). Park et al. (2023) applied deep CNNs to over 150,000 radiographs and achieved 98.5% classification accuracy, highlighting the scalability of AI in real-world settings.[6] Similarly, Sukegawa et al.

(2023) used ResNet-152 and attained an impressive 98.41% identification rate on 9767 radiographs.[5] These applications are particularly useful in cases where patient records are unavailable or incomplete, thereby streamlining treatment planning and follow-up care.

4.2. Surgical Planning and Anatomical Segmentation

AI's ability to automatically identify critical anatomical landmarks such as the mandibular canal, maxillary sinus, and bone thickness is revolutionizing preoperative workflows. Studies using U-Net and DeepLab3 architectures showed precise segmentation, drastically reducing manual labor and potential human error.[3][11] Macrì et al. (2024) reported that AI-based planning was up to 116 times faster than manual methods, offering clinicians efficient and accurate tools.[3]

4.3. Predictive Models for Peri-Implantitis

AI has shown considerable success in predicting peri-implant disease by analyzing clinical and radiographic data. Logistic regression, random forest classifiers, and support vector machines were employed in multiple studies with prediction accuracies up to 90%.[13][14] Yildirim et al. (2023) demonstrated that combining periodontal parameters with radiographs enhances the sensitivity of AI models in identifying early inflammatory signs.[14] These tools offer a proactive approach to managing peri-implant health, allowing clinicians to tailor preventive interventions.

4.4. AI in Implant Design and Stress Optimization

Finite Element Analysis (FEA) integrated with AI techniques is facilitating the development of optimized implant designs that enhance osseointegration and reduce biomechanical stress.[10][15] In one study, implants designed using AI-driven FEA showed a 36.6% reduction in stress concentration compared to conventional designs.[10] These innovations pave the way for fully customized prosthetic solutions tailored to each patient's anatomical and functional demands.

5. Challenges and Limitations

Despite the promising results, several challenges remain in the clinical translation of AI in implantology:

- Dataset Heterogeneity: Most AI models are trained on geographically and demographically limited datasets, restricting their generalizability.[1][5]
- Lack of External Validation: Few studies performed multicenter validations or prospective trials to test AI models in diverse clinical settings.[2][6]
- Algorithm Transparency: The "black-box" nature of deep learning models hinders clinical trust and accountability.[13]
- Ethical and Legal Concerns: AI systems raise issues around informed consent, data privacy, and algorithmic bias.[16][17]

Furthermore, clinician skepticism and limited AI literacy among practitioners can hinder adoption, reinforcing the need for structured training and interdisciplinary collaboration.

6. Clinical Implications

AI presents the potential to act as a robust decision-support tool in implant dentistry. From automatic diagnosis to real-time surgical guidance and predictive analytics, AI can substantially enhance diagnostic precision, treatment planning efficiency, and long-term patient outcomes. However, safe and ethical deployment depends on developing regulatory frameworks, creating standardized benchmarks, and ensuring AI transparency.

7. CONCLUSIONS

Artificial intelligence has demonstrated significant advancements in various areas of dental implantology, including:

- Accurate implant system recognition using CNNs.[5][6]
- Enhanced anatomical segmentation and planning with deep learning models.[3]
- Predictive tools for peri-implant disease using machine learning algorithms.[13][14]
- Optimized implant designs through AI-integrated finite element modeling.[10]

Despite these developments, limitations related to dataset diversity, clinical validation, algorithm explainability, and ethical concerns remain barriers to widespread adoption. Future research should focus on multicenter clinical trials, open-access annotated datasets, and cross-disciplinary standards to transition AI from experimental use to clinical mainstream.

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