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Applications of Artificial Intelligence in Implant Dentistry: A Systematic Review

Sharwari P Bhatkar[1], Krishankumar Lahoti[2], Roshni Taori [3], Vaishnavi Mohite[4], Rutuja Deshmukh[5], Mayur Chakole[6]

[1][2][3][4][5]Post Graduate Student, Department Of Prosthodontics And Crown And Bridge, Swargiya Dadasaheb Kalmegh Smruti Dental College And Hospital, Nagpur.

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KEYWORDS

Artificial Intelligence, Implant dentistry, Convolutional neural networks, Deep Convolutional neural networks, Artificial neural network

ABSTRACT:

Introduction: The integration of artificial intelligence (AI) in healthcare has significantly transformed various fields, including dentistry. This systematic review explores the applications of AI in implant dentistry, focusing on its impact on diagnosis, treatment planning, and post-treatment monitoring.

Methods: : An electronic literature search was carried out through PubMed, Google Scholar, K-HUB, Prosquest, and Cochrane Review databases from the year 2005 to 2024 by two independent investigators. The comprehensive search was restricted to the studies published in the English language from the year of origin of the earliest studies to identify and collect evidence that answers the PICO questions.

Results: Twenty articles were included: 13 investigations analysed AI models for implant type recognition, 5 studies included AI prediction models for implant success forecast, 1 study evaluated AI models for optimization of implant designs using FEM analysis and 1 study analysed osseointegration.

Conclusions: This systematic review highlights the transformative role of artificial intelligence (AI), particularly deep learning and CNNs, in implant dentistry—enhancing diagnostic accuracy, treatment planning, and implant design with performance that often exceeds human expertise. While AI shows great promise, especially with the use of large imaging datasets like CBCT, ethical considerations such as data privacy, bias mitigation, and transparency are essential to ensure its responsible integration alongside clinical expertise.

1. Introduction

Artificial Intelligence (AI), introduced in 1956 at Dartmouth University, has rapidly evolved into a cornerstone of modern computer science. Defined as "the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages," AI encompasses various subfields, including artificial neural networks (ANNs), deep learning (DL), machine learning (ML), and robotics (1). These technologies have seen increasing applications across diverse domains, including dentistry and medicine.

Among AI methodologies, ANNs—comprising an input layer, an output layer, and multiple interconnected neurons—are foundational. A prominent subtype, convolutional neural networks (CNNs), excels in processing complex datasets through unique neuron structures and convolutional mathematical operations. CNNs are widely used in dentistry to analyse data such as case notes, radiographs, and even audio inputs. They operate in two distinct phases: a training phase, where data patterns are learned, and a testing phase, where predictions are made using new, unseen data (2).

In dentistry, the development of advanced dental implant systems (DISs) has focused on enhancing implant-bone interactions through innovations in surface coatings, tapered designs, thread types, and apex modifications. These advancements aim to improve primary stability and accelerate osseointegration, making dental implant

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surgery a highly reliable treatment for edentulous patients [3, 4]. However, the success of dental implant procedures is influenced by patient-specific factors such as bone quality, anatomical considerations, and preoperative planning [5].

Cone beam computed tomography (CBCT) imaging has become an indispensable tool in implant dentistry, providing accurate three-dimensional visualizations of oral and maxillofacial structures with minimal radiation exposure [6]. Despite its utility, the success of implant surgeries often depends on clinicians' subjective evaluations of anatomical variations, bone density, and quality [7]. Challenges such as implant superstructure complications, peri-implantitis, and failures require precise preoperative assessments and effective treatment strategies [8, 9, 10]. Additionally, retrieving key details about previously placed implants, such as manufacturer and system type, is often difficult, leaving clinicians reliant on radiographs and their experience to identify implant systems [11].

Dental implant failure remains a significant concern, often resulting from low bone volume, poor bone quality, periodontal loss, or systemic conditions such as diabetes and osteoporosis. Early detection and prediction of potential complications are critical to preventing adverse outcomes. Factors such as smoking, infection, implant placement technique, and underlying health conditions further underscore the need for advanced predictive methods [12].

Recent advancements in AI and machine learning (ML) have shown promise in addressing these challenges. AI algorithms can analyse CBCT images, extracting clinically relevant data to enhance decision-making processes and improve prediction accuracy [13]. For instance, one study demonstrated that combining early-stage trabecular bone characteristics with ML algorithms significantly outperformed traditional methods in predicting marginal bone loss [14]. Similarly, AI applications in implant dentistry have explored the classification and identification of dental implants using radiographic modalities such as periapical and panoramic images [11, 14].

These advancements underscore the potential of AI to transform implant dentistry by improving predictive accuracy and optimizing clinical outcomes. This systematic review aims to evaluate the current applications of AI in dental implantology, focusing on its utility in predicting implant success and addressing associated challenges.

2. Methods

<u>Aim And Objectives-</u>

Aim-

The aim of this study is to assess the applications of Artificial Intelligence in implant dentistry.

<u>Study Design-</u>

Studies included in this systematic review are Randomized controlled trials, in vivo studies and invitro studies.

<u>Material And Methodology</u>

<u>Protocol And Registration-</u>

The Prisma (The Preferred Reporting Items For Systematic Reviews And Meta-Analyses) Guidelines Were Followed To Report This Systematic Review.

This Review Is Registered On Prospero. (Registration No.-CRD42024499089)

Eligibility Criteria-

The search strategy was conducted through PubMed, Google Scholar

And Cochrane which was based on the research question:

What are the applications of Artificial Intelligence in implant dentistry?

<u>Study Protocol</u>

Before the start of the systematic review, a protocol was developed and registered (Prospero ID - CRD42024499089) Aiming To Answer The P.I.C.O. Questions that rendered the following P.I.C.O. definitions;

<u>Population:</u> The Population Included The Clinical Applications In Implant Dentistry For Implant Type Recognition, Osteointegration Success Or Implant Success Prediction By Using Patient Risk Factors And Ontology Criteria, And Implant Design Optimization By Combining Fea Calculations And Artificial Intelligence models.

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Intervention: The Intervention Included Artificial Intelligence Models.

Comparisons: The Comparison Was Determined As Nonapplicable.

Outcomes: The outcome was the Artificial Intelligence model performance for recognition of the implant type, forecast of the implant success by using patient risk factors and ontology criteria, and optimisation of implant designs by combining FEA calculations and Artificial Intelligence models.

Information Sources-

An electronic literature search was carried through PUBMED, GOOGLE SCHOLAR, K-HUB, PROQUEST and COCHRANE REVIEW databases from the year 2005 to 2024 by two independent investigators. The comprehensive search was restricted to the studies published in English language from the year of origin of the earliest studies to identify and collect evidence that answers the PICO questions.

Search Strategy-

The studies to be included in present systematic review were searched by two

independent reviewers and in case of discrepancy , a third examiner intervened

to resolve the difference in opinion. The electronic database used for the search was PubMed, Google scholar and Cochrane library. Boolean operator "AND" and "OR" was used to search PubMed articles.

Terms like "Dental Implant" "Artificial Intelligence" "Machine Learning" "Deep Learning" " Convolutional Neural Networks" "Artificial Neural Networks" was used.

Mesh terms for both was retrieved from PubMed and was used with Boolean operator "OR" When looking in Google Scholar the Boolean terms were replaced by "+."

For Cochrane library "Applications of Artificial Intelligence In Implant Dentistry" in all text was used.

Study Selection-

Identification-

Database search was performed by two independent reviewers and the articles were first selected by reading the titles and abstracts. The duplicate search was removed.

Screening-

Two independent reviewers screened the identified publications based on the following criteria:.

Subsequently, manual search was conducted based on the reference list

of selected studies and relevant reviews to identify studies that were not indexed

in the above databases: International Journal of Prosthodontics and Restorative Dentistry, Journal of Prosthetic Dentistry, The International Journal of Prosthodontics, The Journal of Indian Prosthodontic Society, Journal of Dentistry, Journal of Dental Research, Clinical Implant Dentistry and Related Research,

Studies To Be Included As Per Formal Screening

1. Randomized controlled trials.
2. In vivo animal and human studies.
3. Invitro Studies
4. Case Report, Randomized Control Trials, and Reviews describing the Applications of Artificial Intelligence in Implant Dentistry
5. Studies conducted from 2005 to 2024 will be included in this study.

Studies To Be Excluded As Per Formal Screening

1. Unpublished studies, case reports, case series, abstracts, textbooks, narrative reviews, and expert opinions will be excluded.
2. Articles Published In Different Languages Than English
3. Studies Not Describing Applications Of AI In Implant Dentistry,
4. Studies Describing Implant Treatment Without The Use Of Artificial Intelligence In Randomized Control Trials
5. Studies Having Follow Up Period Of Less Than 1 Year,

6. Articles Before The Year 2005 Will Be Excluded From The Study.

7. Studies not meeting the inclusion criteria.

Eligibility-

The full texts of selected studies were acquired and the reference lists of all the primary articles were screened for any additional relevant studies. All the full text articles were analysed by two independent reviewers for final eligibility in the systematic review.

Data Extraction /Data Collection Process-

Two review authors independently reviewed and assessed all titles and abstracts of studies retrieved in the search for inclusion. In cases of disagreement, a third author was consulted.

A manual search was also conducted, including reference lists and grey literature such as unpublished studies, theses, and dissertations, to reduce publication bias. Discrepancies were resolved by discussion, and authors were contacted for clarification if needed.

Data from selected studies were extracted using standardized forms, adjusting for differences in study design and outcomes. The authors independently compiled key data, evaluated article quality using predetermined criteria, and assessed the risk of bias using the Cochrane handbook. The quality of evidence was graded using the GRADE system.

3. Results

Study Selection

A Comprehensive Search Of Multiple Databases Yielded 753 Articles. Two Independent Reviewers Identified Relevant Articles, Removing 678 Duplicates. After Screening Titles And Abstracts, 75 Articles Were Selected For Full-Text Evaluation. For Non-English Publications, Corresponding Authors Were Contacted For Translations. The Eligibility Of Studies Was Determined Using Specific Inclusion And Exclusion Criteria.

After Thorough Review Of The Methodology Sections, 55 Articles Were Excluded For Not Meeting The Criteria, Leaving 20 Relevant Publications For Inclusion In The Systematic Review. Few Systematic Reviews On The Topic Were Found. Data From The 20 Selected Studies, Mostly Conducted In India And Published In English, Were Critically Analysed For Quantitative And/or Qualitative Assessment.

Study Characteristics

The Characteristics Of The 20 Included Studies In This Systematic Review Are Given In The Results Of The Individual Studies.

Data Collection

Information Related To The Study, Including Study Design, Method Of Randomization, Description Of Population, Sample Size, Details Of Inclusion And Exclusion Criteria In Study, And Control Group, Was Obtained. The Record Of The Study Included Details Of Types Of Radiographs, Types Of Algorithm Architecture, Types Of Dental Implant Systems, And The Number Of Patients.

Risks Of Bias Within The Studies:

The Majority Of The Studies Included In This Systematic Review Have Been Rated As "Low" Risk Of Bias, Indicating That They Have Data Selection, Index Test, Reference Standard, Flow & Timing, Data Selection, Index Test, Reference Standard. This Suggests That The Overall Risk Of Bias In The Systematic Review Is Likely Low, With Reliable Evidence From The Included Studies.

Quality Assessment Of The Studies

Study Quality Varied Considerably, And Out Of A Total Possible Qatsdd Score Of 42, Scores For The Individual Studies Ranged From 13 To 38. The Average Score Was 18.9 (6.4). Table Shows The Mean Score For Each Of The 14 Criteria Of The Quality Assessment. A Mean Score Of 0 Indicates None Of The Papers Met Any Of The Components Of The Criteria, With A Total Possible Score Of 3 Indicating All The Papers Fully Met The Criteria.

Some Quality Criteria Were Well Addressed By The Included Studies, Particularly The Alignment Between The Research Question And Methods Of Data Collection And Analysis. However, none of the papers showed evidence of user involvement in the design, and most of them lacked an explicit theoretical framework. Two Other Areas With Weaker Coverage Were Sample Size

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Estimation And The Assessment Of The Reliability And Validity Of Measurement Tools.

For Quality Assessment, Independent Reviewers Agreed On 206 Of 280 (73.5%) Quality Criteria Scores. A Weighted Kappa Was Performed To Measure Relative Concordance Between Reviewers, Assuming Equal Differences Between Scores. The Inter-Rater Agreement (Kappa With Linear Weighting) Was 0.77 (95% Ci, 0.63–0.88), Indicating Substantial Agreement.

4. Discussion

Since 2018, the use of artificial intelligence (AI) in implant dentistry has expanded significantly, with a strong focus on applying Convolutional Neural Networks (CNNs) and deep learning to radiographic images for identifying implant types. Although studies have demonstrated remarkable accuracy (93.8% to 98%) in these models, comparing results remains challenging due to varying methodologies. Most research relies on 2D radiographs, but integrating 3D CBCT scans could improve accuracy further [41].

The Key Developments in AI Applications are as follows:

A. Radiographic Image Analysis:

Kim JE et al. demonstrated that a small CNN could classify four implant fixture types using limited images, achieving high accuracy while reducing the need for extensive datasets. This method also helps avoid unnecessary procedures and costs by identifying implant types with minimal radiographic input. The study emphasised focusing on single-implant images and periapical radiographs while advocating for networks capable of classifying implants from panoramic radiographs due to their frequent use in clinical settings [25].

Combining imaging formats, as shown by Oh S et al., improved predictive accuracy. Their deep learning model achieved 87% accuracy by integrating periapical and panoramic images, effectively distinguishing between implant failures with and without marginal bone loss, thus enabling targeted treatment planning [44].

B. Performance of Advanced Architectures:

Lee JH et al. utilised the Google Net Inception-V3 architecture to classify dental implant systems (DISs) with an AUC of 0.956 to 0.979, outperforming board-certified periodontists (AUC 0.891 to 0.959). The model excelled with Straumann BLT implants due to their larger taper and consistent structural features across datasets. However, variation in implant structure, such as differences in length and diameter within the same system, remains challenging. [31].

Takahashi T et al. further demonstrated the reliability of automated systems, achieving high accuracy with deep learning models across different images and implant systems. Metrics like mean average precision (mAP) and mean intersection-over-union (mIoU) highlighted the system's efficacy in overcoming manual classification limitations [30].

C. Advancing Predictive and Design Capabilities:

Beyond classification, AI models now aid in predicting implant outcomes and optimizing designs. Oh S et al. integrated radiographic data to enhance accuracy in predicting implant failures, providing a comprehensive view of the implant and surrounding structures. Similarly, finite element analysis (FEA) combined with AI has been utilized to refine implant designs and reduce stress at the implant-bone interface [41, 44].

Challenges and Opportunities

Several limitations persist in current AI applications:

1. Limited Implant Types and Data: Many studies focus on specific implant systems, restricting generalizability. Expanding datasets to include more diverse implant types is essential [25, 31].

2. Rare Implant Failures: Addressing rare conditions, such as implant fractures, requires robust datasets and advanced algorithms [41].

3. Integration of 3D Imaging: While most studies rely on 2D radiographs, incorporating 3D CBCT scans offers the potential to improve diagnostic accuracy by providing comprehensive spatial data [41].

Future advancements should aim to develop networks that classify implants by size, length, and type from panoramic radiographs, given their common use in treatment planning [25]. Moayeri RS et al. emphasized combining algorithms to improve detection rates for unsuccessful implantations while integrating lifestyle factors such as alcohol consumption and betel nut

chewing—significant contributors to late fixture failure—could further refine predictive models (11, 21).

Conclusion

This systematic review evaluated the applications of artificial intelligence (AI) in implant dentistry, highlighting its transformative potential. AI, particularly deep learning and CNNs, is revolutionizing the field by delivering exceptional accuracy and efficiency, often outperforming dental experts in classification tasks. As advancements continue to address current limitations, AI is poised to enhance diagnostic precision, treatment planning, and implant design, ultimately redefining clinical practice (27, 37).

Overall, AI has demonstrated promising results, especially with the development of larger databases incorporating periapical and cone beam computed tomography (CBCT) imaging. These advancements underscore the significant potential for future research in AI applications for implant dentistry.

However, ethical considerations remain pivotal. Safeguarding patient data privacy, mitigating biases in training datasets, and ensuring transparency in AI-driven decision-making are essential to fostering trust and equitable outcomes. Importantly, AI should serve as a complementary tool, enhancing clinical expertise while preserving the critical role of the clinician in patient care.

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