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Artificial Intelligence in Periodontology and Implantology: A Narrative Review

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Abstract

Artificial intelligence (AI) has become an influential tool in periodontology and implantology; enhancing diagnostic & prognostic accuracy, supporting digital workflows, and improving clinical decision-making. Artificial intelligence is reshaping how clinicians assess, plan, and execute treatments. To provide a comprehensive and clinically relevant overview of current AI applications in periodontology and implantology, evaluate their benefits ,limitations, and possible future directions .This narrative review synthesizes findings from 111 studies including; recent human studies, systematic reviews, and clinical trials exploring technology-driven research exploring AI in diagnostic imaging, periodontal risk prediction, digital implant planning, surgical navigation/robotics, regenerative decision-making, and natural language processing tools. AI demonstrates high diagnostic performance in radiographic interpretation, with reported accuracies ranging from approximately 76% to over 90% depending on tooth type, dataset characteristics, and model architecture. Deep learning models have shown performance comparable to experienced clinicians in controlled experimental settings, particularly in retrospective radiographic datasets. Machine-learning risk assessment models offer personalized predictions for disease progression and implant complications contributing positively to patient centered care. In implantology, AI supports CBCT segmentation, implant position optimization, enhances accuracy through navigation and provides robotic assistance. Emerging applications include automated gingival phenotype assessment, outcome prediction for regenerative procedures, and natural language processing to assess patient/clinician notes. Limitations include dataset bias, lack of external validation, inconsistent reporting standards, and ethical concerns related to transparency and clinical accountability.

AI is rapidly advancing across periodontal and implant disciplines, showing potential to improve diagnostic consistency and treatment planning. However, current evidence remains heterogeneous and is largely derived from retrospective or preclinical studies, limiting immediate clinical translation. Further prospective, multicenter validation studies are required before routine clinical implementation.

1 Introduction

Artificial intelligence (AI) is the ability of computer systems to perform tasks associated with human intelligence. AI has become integrated in many disciplines, and dentistry is no exception [1]. AI-driven technologies can simulate clinical reasoning and support dentists in the diagnosis and management of oral diseases such as periodontitis, a highly prevalent inflammatory condition that destroys the supporting structures of the teeth [2].In periodontology, the incorporation of AI represents a major opportunity to improve early disease detection, sharpen diagnostic

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accuracy, and tailor treatment planning for individual patients [1, 2, 3]. Conventional diagnostic approaches depend greatly on clinician's subjective judgment and are therefore susceptible to examiner variability or bias, which can influence consistency and quality of care. AI-based tools have shown potential to enhance diagnostic precision and support personalized treatment strategies; however, their performance remains dependent on dataset quality, model design, and validation methodology [4]. In particular, machine learning and deep learning models can process complex clinical and radiographic datasets, opening new avenues for more robust diagnostic workflows and data-driven treatment decisions in periodontics [5]. This review examines the applications of AI in periodontology and implantology, with a focus on current applications and emerging directions that may reshape clinical practice.

The artificial intelligence applied to periodontology and implantology is dominated by machine learning (ML), where patterns from data are detected and translated to algorithms to perform classification, regression, or prediction tasks without programming [6, 7, 8, 9]. Within ML two modes exist ;supervised learning where models are trained on labeled datasets, such as radiographs annotated for periodontal or peri-implant bone loss, disease stages, or implant success, and then applied to unseen cases to detect bone defects, quantify marginal bone levels, or predict disease progression are more commonly used [10, 11, 12, 13, 14, 15, 16, 17]. In contrast, unsupervised learning techniques are used to detect patterns in unlabelled complex clinical, microbiological, or behavioral datasets which may lead to more individualized periodontal risk stratification and recall protocols ; sometimes both Supervised and unsupervised learning are employed within the same study for maximum detection [2, 18, 19]. The most powerful AI models are based on deep learning (DL), particularly convolutional neural networks (CNNs), which automatically learn image features to detect objects such as teeth /implants, segment the images for instance into alveolar/ peri-implant bone, identify specific parts such as furcation and intrabony defects, and automatically measure outcomes such as bone loss on periapical, panoramic, and CBCT images; with several studies reporting performance comparable to expert examiners under controlled experimental conditions, although variability exists across datasets and clinical scenarios [20, 21, 22, 23, 24, 25, 26, 27].

Beyond imaging, natural language processing (NLP) focuses on text in electronic dental records, using transformer-based architecture models to automatically extract periodontal diagnoses, probing depth patterns, bone loss descriptors, and risk factors from narrative clinical notes or structured data fields, to enable phenotyping and evidence generation from a large amount of patient data that is otherwise overlooked [28, 29, 30, 31]. Reinforcement learning (RL) concepts include decision-making and robotic assistance, where implant drilling trajectories, prosthetic adjustments, or maintenance scheduling is optimized according to predefined reward functions related to accuracy, safety, and long-term stability; contributing to the rapidly evolving field of dental robotics ,guided and autonomous implant placement [32, 33, 34, 35, 36]. More recently, large language models (LLMs) and generative/multimodal AI capable of integrating imaging, clinical variables, and textual data, supporting case-level reasoning, patient-specific education, and decision support have emerged [37, 38, 31, 39, 40]. All of these AI subtypes form a complementary tool-kit that aids in data-driven diagnosis, risk prediction, and treatment planning in periodontology and implant dentistry [1, 3, 2, 5, 4].AI systems have demonstrated diagnostic accuracies, sensitivities, and specificities comparable or surpassing, experienced dental professionals in the field of periodontology [41].

2 Materials and Methods

This narrative review was conducted to provide a clinically oriented overview of artificial intelligence applications in periodontology and implantology. A structured literature search was performed in PubMed/MEDLINE, Scopus, and Google Scholar for studies published up to December 2025, using combinations of the terms 'artificial intelligence,' 'machine learning,' 'deep learning,' 'periodontology,' 'periodontitis,' 'implantology,' 'dental implants,' 'radiographic bone loss,' 'peri-implantitis,' 'natural language processing,' and 'robotics.' Priority was given to peer-reviewed English language articles with direct relevance to periodontal and implant applications, particularly systematic reviews, clinical studies, validation studies, and high-quality original research. Editorials, duplicate reports, non-dental studies, and sources lacking sufficient methodological detail were excluded or used only sparingly when discussing emerging technologies. The search yielded 111 studies. Where available, emphasis was placed on studies reporting quantitative performance metrics (e.g., accuracy, sensitivity, specificity, AUC) to support evidence-based synthesis.

3 Results

3.1. AI in Periodontal Diagnostics and Prognosis

The diagnostic capabilities of AI extend to the detection of periodontal bone loss, with models using panoramic radiographs demonstrating improved diagnostic performance compared to conventional approaches in specific experimental settings, particularly in radiographic analysis tasks [42]. These AI-driven analyses can accurately quantify alveolar bone levels, identify subtle changes indicative of early disease, and predict disease progression, leading to more timely and effective interventions [42, 43]. Deep learning convolutional neural networks, have proven particularly effective in interpreting dental images, detecting signs of inflammation, calculus, recession, bleeding, and bone loss from intraoral photographs and cone beam computed tomography scans [44, 10]. AI models have also demonstrated high precision in segmenting crucial periodontal structures like the cemento-enamel junction and alveolar bone level from radiographs, surpassing prior models in robustness and accuracy to minimize misdiagnosis that was found in older models [45, 46]. This advanced segmentation allows for a more objective assessment of periodontal health, reducing the subjectivity often associated with manual interpretations [42]. Such sophisticated AI models are capable of identifying multiple pathologies simultaneously, and enhancing clinical workflows by enabling practitioners to work with greater speed and precision while increasing sensitivity to certain conditions [22]. Enhanced diagnostic capability, especially with panoramic radiographs, has led to a significant reduction in diagnostic errors and inconsistencies that were previously common with conventional methods, that relied heavily on clinical examinations and subjective radiographic interpretations [42]. Furthermore, AI algorithms can recognize subtle patterns and indicators of disease within large datasets, analyzing radiographs to identify minor changes in bone and periodontal tissue that might be missed by human observation, thereby aiding in early diagnosis and treatment planning [47, 6]. AI's capacity for multimodal data integration, including clinical measurements, medical history, and 3D scans, revolutionizes diagnostic accuracy and treatment planning in periodontology [44]. Comprehensive risk assessment that contributes to the development of highly individualized therapeutic approaches, allows a more proactive and preventive paradigm in standard periodontal care [42, 45]. Despite these promising findings, most studies are retrospective and rely on limited or institution-specific datasets, which restricts external validity. Additionally, differences in annotation protocols, imaging modalities, and evaluation metrics make direct comparison between studies challenging.

3.2. AI Models for Disease Detection and Diagnosis

Artificial intelligence has significantly advanced the diagnostic capabilities in periodontology by enabling the precise detection of various periodontal conditions and aiding in prognosis [48, 45]. These advancements span from analyzing dental images to streamlining administrative tasks [47], AI-powered systems can meticulously analyze radiographic images to detect subtle signs of periodontal bone loss and identify periodontally compromised teeth with high sensitivity and specificity [49, 50]. This analytical prowess extends to evaluating prognostic factors, where AI models can predict the likelihood of disease progression or treatment success by integrating patient data, genetic predispositions and systemic health indicators [51]. These models use advanced machine learning techniques to correlate complex datasets, including oxidative stress markers, with disease progression, to allow a more profound understanding of periodontal pathogenesis than single gene markers alone [52]. For instance, deep learning models can be trained on extensive datasets of patient records, radiographs, and clinical parameters to accurately classify periodontal disease severity and predict future outcomes with remarkable precision [53]. This capability allows clinicians to intervene proactively, tailoring treatment plans to individual patient needs and optimizing therapeutic outcomes [18]. Such AI-driven predictive analytics not only enhance the accuracy of prognoses but also contribute to the developing preventive strategies for peri-implant diseases, identifying high risk patients and refining management protocols [44].

Beyond diagnostics, AI algorithms can also discern subtle patterns within routine blood tests to predict periodontal disease risk, offering a valuable tool for early detection and prevention in diverse healthcare settings [5]. The utility of AI in periodontology is further demonstrated by its capacity to analyze various clinical parameters, such as probing depths, gingival inflammation, and attachment loss, to predict and diagnose periodontal disease with high accuracy [54]. For example, research has shown that decision trees, Support Vector Machines, and neural networks can classify periodontal diseases with some studies reporting accuracies exceeding 90% under controlled conditions; however, such results are often influenced by dataset size, class imbalance, and model training conditions [55, 56]. Similarly, deep convolutional neural networks have shown comparable performance to experienced periodontists in predicting periodontal disease using radiographic images, achieving up to 81.0% accuracy in premolar and 76.7% in molar teeth [55, 56]. These models can be trained on extensive patient data, incorporating clinical, demographic, and salivary analyte parameters, to construct predictive models for periodontitis progression [41]. This integration of diverse data types, including omics data and biomarker analyses, enables AI to construct comprehensive diagnostic markers and prognostic models that are crucial for personalized treatment approaches [52, 57]. Shifting towards precision periodontics, with treatments tailored to the individual patient's molecular and clinical profile, enhancing therapeutic efficacy and patient outcomes [51].

3.3. AI for Bone Loss Assessment

Some AI algorithms have been specifically engineered to quantify and monitor bone changes around teeth with exceptional precision across various imaging modalities; convolutional neural networks have been successfully used to identify periodontally risky teeth from periapical radiographs, classifying them into healthy, moderate, and severe categories with significant accuracy [49]. Automatically detecting and quantifying alveolar bone loss in two-dimensional (2D) radiographs, models demonstrate performance comparable to human evaluators in specific radiographic tasks, although results vary depending on imaging modality, defect type, and model generalizability [10, 16]. This includes frameworks that combine YOLOv8 for tooth detection with Keypoint R-CNN models for identifying anatomical landmarks, enabling precise calculation of bone loss severity and pattern analysis [46, 58]. These sophisticated systems can delineate the exact extent of bone loss, distinguish between different types of bone defects, and even predict the future trajectory of bone resorption, providing more objective and consistent assessment than traditional methods [44]. AI-driven models utilizing Convolutional Neural Networks have also been developed to accurately assess alveolar bone loss and provide individualized periodontal prognoses from panoramic radiographs, overcoming the subjectivity and labor-intensity of traditional methods [42, 45]. Such advancements enable more reliable radiographic bone-loss measurements and image-based periodontal diagnoses, thereby enhancing clinical decision-making for managing periodontal disease [48].

Beyond periodontal applications, AI's role in assessing bone quality and quantity is crucial for implant dentistry, where algorithms can analyze CBCT scans to optimize implant placement and predict osseointegration outcomes [30, 21]. This is achieved by machine learning systems that analyze anatomical data and patient history to suggest optimal implant positions and sizes, contributing to more predictable surgical outcomes [7]. Deep learning models can accurately detect and classify periodontal bone loss from panoramic radiographs, offering a two-stage system first identifying the presence of bone loss and then localizing & classifying extent [15]. One such system that uses a Mask R-CNN-based network to segment and measure bone loss, demonstrates high precision in identifying regions of interest and quantifying bone levels [11]. Another model utilizing a YOLO-v5 framework has achieved high effectiveness in detecting alveolar bone loss across different regions in panoramic radiographs, particularly excelling in maxillary areas [12]. Additionally, AI models trained on periapical radiographs can automatically detect and quantify the severity and patterns of alveolar bone loss, which is critical for differential diagnosis and treatment planning [58]. These sophisticated AI systems significantly reduce the time and labor involved in radiographic assessment, ensuring greater consistency,reproducibility, and objectivity compared to manual clinician analysis [14, 13]. The integration of these AI-powered diagnostic tools promises to revolutionize periodontal and implant therapy by providing a more efficient, accurate, and consistent approach to identifying and managing bone loss [45, 20].

3.4. Predictive Analytics for Treatment Outcomes

AI's predictive capabilities include predicting the success rates of various periodontal and implant treatments, by analyzing vast datasets of patient responses to different therapeutic interventions [59]. This involves leveraging machine learning algorithms to process intricate patient data, including genetic predispositions, systemic health conditions, and treatment protocols, to forecast long-term outcomes for both periodontal therapies and dental implant procedures [9, 60]. These predictive models can evaluate factors like bone density, implant length, and diameter to anticipate implant success rates, thereby guiding clinicians in making informed decisions during treatment planning [61]. AI algorithms can also predict the risk of developing peri-implantitis and other implant complications, enabling early intervention and personalized preventative strategies to improve long-term implant survival [60, 17]. In periodontology, AI can predict the stability of periodontal tissues after regenerative procedures by analyzing inflammatory markers and microbial profiles, offering a more nuanced understanding of healing potential and recurrence risk. AI Models are also able to forecast the efficacy of various interventions, including non-surgical periodontal therapy, surgical approaches, and the long-term prognosis of teeth affected by periodontal disease [3].

In implant dentistry, AI-driven predictive modeling can assess the likelihood of osseointegration and long-term implant stability by integrating patient-specific physiological data with biomechanical properties of the implant [62], assisting clinicians in selecting appropriate implant designs and materials, as well as in devising individualized loading protocols to enhance implant longevity and reduce failure rates [63, 64]. Artificial neural networks with memetic search optimization can predict dental implant success rates with high efficiency by simultaneously evaluating patient data, implant systems, and surgical operations [61]. Hybrid machine learning models combining decision trees and neural networks have shown promise in predicting implant success based on a comprehensive set of pre-operative and intra-operative variables [60]. These sophisticated models contribute to a more personalized and evidence-based approach to implant dentistry, enhancing the overall predictability and success of dental implant procedures [60, 65]. Such advanced AI applications offer clinicians unparalleled support in optimizing treatment strategies, leading to improved patient outcomes and more efficient resource utilization in both periodontology and implantology [1, 66.]

3.5. AI in Implant Dentistry: Planning and Execution

The integration of artificial intelligence into implant dentistry has the potential to transform diagnostic processes and treatment planning, although most applications remain in early-stage or experimental phases, possibly introducing an era of enhanced precision and personalized patient care [67, 26]. AI models can refine implant success predictions by analyzing cone-beam computed tomography images to segment anatomical structures and detect bone quality, which is crucial for surgical planning [31].Accurate assessment of bone quality and quantity, and identification of vital structures, by AI models decreases surgical risks and optimizes implant position for ideal prosthetic outcomes [61]. Moreover, AI can virtually simulate implant placement, allowing clinicians to refine treatment strategies and make necessary adjustments before actual surgical intervention, improving accuracy and predictability and faciliting patient education, by allowing individuals to visualize their treatment journey and expected outcome [64]. AI-powered surgical guides, including static, dynamic, and robotic systems, have transformed implant placement procedures [64]. These innovations not only enhance the precision of surgical interventions but also significantly reduce operative time and potential complications, leading to improved patient safety and recovery [61]. AI models can also predict potential complications and recommend preventive measures, further enhancing the safety and efficacy of implant procedures [64, 68].

3.6. Intraoral Scanner Integration with AI

Intraoral scanners with AI algorithms significantly enhance diagnostic accuracy and treatment planning in implant dentistry by generating highly precise 3D models of the oral cavity [25]. These models, when analyzed by AI, can identify subtle discrepancies, measure tissue volumes, and predict post-surgical contours, enabling a more predictable and aesthetically pleasing outcome for prosthetic restorations [25]. This advanced integration streamlines the workflow from digital impression to final restoration, minimizing human error and maximizing efficiency [69]. Beyond mere efficiency, AI-powered analysis of intraoral scan data can automatically detect pathological conditions, assess periodontal health, and even predict potential implant complications by identifying areas of insufficient bone density or anatomical variations [64]. Furthermore, AI models trained on large datasets from intraoral scans can precisely segment anatomical structures and accurately measure alveolar bone dimensions, crucial for virtual implant planning and custom surgical guide fabrication [27].

AI models are able to integrate data from various sources, such as intraoral scans and CBCT, allowing for a comprehensive virtual patient model, and enhancing treatment predictability [47, 70,71].

3.7. AI-Driven Surgical Guide Design

AI-driven surgical guide design significantly improves the accuracy and reliability of implant placement by utilizing sophisticated algorithms to process anatomical data from CBCT scans and intraoral impressions [72]. Algorithms precisely delineate anatomical structures, identify critical vascular and nervous pathways, and compute optimal implant trajectories, thereby minimizing surgical risks and enhancing procedural safety. This advanced computational approach ensures that each surgical guide is custom-tailored to the patient's unique anatomy, allowing for predictable and precise implant positioning [13]. By integrating machine learning algorithms, AI can further optimize guide design by analyzing historical surgical outcomes and incorporating feedback to refine implant angulation and depth for improved long-term success rates [54,73]. Furthermore, AI-enhanced CAD/CAM systems now automate the generation of restoration designs by analyzing extensive dental images and patient data, optimizing both aesthetics and functional requirements [74, 31].

3.8. Static and Dynamic Navigation Systems

Static and dynamic navigation systems, increasingly augmented by AI, offer distinct advantages in guiding implant placement with enhanced precision and reduced intraoperative complications compared to traditional freehand methods [35]. Static navigation, often employing patient-specific surgical guides, relies on pre-operative planning to dictate implant position, angulation, and depth, while dynamic navigation provides real-time, intraoperative guidance using optical or electromagnetic tracking systems [47, 75]. AI integration further refines both static and dynamic systems by optimizing surgical guide design for static navigation and enhancing the real-time feedback mechanisms in dynamic systems through predictive analytics and immediate anatomical correlation [74]. For instance, AI algorithms can analyze bone density variations and surgical instrument movements in real-time, providing surgeons with immediate adjustments to ensure optimal implant direction and reduce the risk of critical structure damage [61]. This integration bridges the gap between theoretical planning and practical execution, significantly improving surgical outcomes and patient safety [76]. The synergy of AI with these navigation technologies allows for adaptive planning during surgery, where AI can dynamically suggest modifications to the original treatment plan based on unforeseen intraoperative findings, minimizing complications and optimizing implant success rates [74]. AI static & dynamic guides have introduced a higher degree of personalization in surgical procedures, by incorporating the unique physiological responses and anatomical nuances of each patient [77].

3.9. Robotics in Implant Surgery

Robotic systems, a further advancement in guided surgery, utilize AI to achieve high precision in controlled environments, although clinical adoption remains limited due to cost, technical complexity, and lack of long-term validation by controlling surgical instruments with precision, surpassing the capabilities of dynamic navigation [35]. Robotics, combined with AI, significantly enhances clinical outcomes, patient satisfaction, and procedural efficiency in implant dentistry by minimizing human error and optimizing placement [78]. These sophisticated systems contribute to reduced surgical trauma, shorter operating times, and accelerated patient recovery [79]. AI's role enables robotic surgery platforms for minimally invasive and highly precise procedures, ensuring better patient outcomes through guided accuracy, however more advanced in the field of medicine than in the field of dentistry [64]. AI-powered robotic systems can analyze vast datasets of prior surgical cases to learn optimal strategies, continually refining their performance and adaptability to diverse anatomical challenges [48]. Robotic systems often incorporate visual, audio, and haptic feedback mechanisms,maintaining operator control and allowing for real-time adjustments and precise drill positioning, which significantly reduces the potential for postsurgical complications [24]. While autonomous robotic systems show promise in improving implant accuracy, current research suggests that further clinical trials are essential to validate their long-term efficacy and safety in various surgical contexts [34]. Beyond surgical applications, medical robots also play crucial roles in diagnosis and rehabilitation, enabling minimally invasive operations that reduce patient trauma and accelerate recovery [33]. AI-driven robotics are making significant strides in orthopedic surgeries, exemplified by systems like MAKO for knee and hip replacements, which utilize AI to create 3D patient joint models for high-precision surgical planning and optimal implant positioning [80]. Similarly, in periodontology and implantology, AI-powered robotics can offer enhanced precision for delicate procedures such as guided bone regeneration or complex implant placements, thereby minimizing soft tissue damage and maximizing osseointegration [80,81,82]. Despite these advancements, practical implementation challenges such as high costs, technical limitations, and the absence of comprehensive haptic feedback mechanisms persist, necessitating sustained research and development [36].

3.10. Analyzing Patient Notes and Electronic Health Records

Natural Language Processing (NLP) plays a pivotal role in extracting valuable insights from unstructured clinical narratives from patient notes and electronic health records, which would otherwise require laborious manual review, facilitating automated analysis for diagnostic support and treatment planning in periodontology and implantology [63]. NLP algorithms can further categorize symptoms, prognoses, and treatment outcomes, to provide a comprehensive overview of patient care that supports evidence-based decision-making. Additionally, NLP can be employed to flag inconsistencies or omissions in patient records, improving data quality and ensuring that all pertinent information is available for clinical evaluation [1]. Moreover, the application of NLP extends to identifying early signs of periodontal disease by analyzing textual descriptions of gingival inflammation, probing depths, and bone loss from clinical notes, thereby facilitating timely intervention [1]. AI allows for a proactive approach to patient management, leading to improved long-term periodontal health outcomes and better prediction of implant success [81]. However, the scalability of such NLP applications in healthcare is often constrained by the extensive manual work required for training and validating machine learning models, limiting the full transformative potential of NLP in clinical settings [30]. As a result, advanced artificial intelligence and natural language processing techniques, including Large Language Models such as GPT-4, are being explored to generate synthetic medical notes for fine-tuning robust models like RoBERTa, which significantly reduces the reliance on extensive manual annotation and addresses data scarcity issues [30, 29]. This innovative approach leverages the strengths of LLMs to produce high-quality, representative datasets, thereby enhancing the accuracy and adaptability of Named Entity Recognition models for extracting complex periodontal diagnoses from clinical text [30]. Synthetic data generation strategy addresses challenges associated with varied formatting and informal diagnostic phrases often encountered in real-world clinical notes, which can hinder model accuracy [30]. The synthetic data approach significantly reduces the institutional-specific biases often found in NLP models trained solely on data from a single facility, thereby increasing the universality and applicability of the resulting diagnostic tools [29, 30]. However, NLP performance is highly dependent on data quality and annotation consistency, and current models may struggle with variability in clinical language and documentation styles.

3.11. Automated Data Extraction and Interpretation

Using NLP capabilities, automated data extraction systems that can process large volumes of clinical text, transforming unstructured notes into structured data points for further analysis and integration into electronic health records have been developed. These systems can identify and extract specific diagnostic codes, treatment plans, and patient outcomes, which are essential for epidemiological studies, quality control, and the development of predictive models in periodontology and implantology [29]. AI-powered NLP tools can significantly enhance the efficiency of clinical workflows by automating the laborious task of data extraction,and allowing practitioners to focus more on direct patient care [29]. The ability to identify missing diagnoses through NLP models, such as Named Entity Recognition, further minimizes diagnostic oversights that may arise from human error or the inconsistent documentation practices inherent in free-text clinical notes [29]. Automated identification of diagnostic omissions contributes to improved data quality, which is crucial for subsequent research and the development of more accurate AI-driven diagnostic and prognostic models [28], vital given the prevalence of unstructured free-text clinical documentation, which, despite its richness, often presents challenges for systematic data analysis and reuse [30]. By converting such qualitative clinical narratives into quantifiable data, AI-driven NLP tools facilitate advanced analytics that can uncover subtle patterns and correlations otherwise imperceptible to human review [28].

3.12. Virtual Reality and Augmented Reality in Dental Education and Practice

Virtual reality (VR) and augmented reality (AR) are rapidly transforming dental education by providing immersive and interactive learning environments, enabling students to practice complex procedures in a risk-free setting [54]. AI offers simulations for training in surgical techniques, implant placement, and periodontal interventions, allowing for reproducible practice and immediate feedback without patient involvement [83, 20]. Beyond education, VR and AR are increasingly being integrated into clinical practice to assist with procedure planning, real-time surgical guidance, and patient communication, ultimately enhancing precision and patient understanding by enabling individuals to visualize complex treatment plans, such as implant procedures, and better comprehend the rationale behind proposed interventions [51,84,85,86]. Moreover, VR and AR technologies facilitate the simulation of various clinical scenarios, including rare or challenging cases, thereby broadening the experiential learning opportunities for dental students and practitioners [87,88,89]. This technological integration allows for the development of adaptive learning modules that cater to individual student needs and skill levels, fostering a more personalized and effective educational experience.

Virtual reality simulations have demonstrated significant potential in enhancing the understanding of complex anatomical structures and surgical pathways, reducing the learning curve for intricate procedures like osseous recontouring and guided bone regeneration [90]. This immersive training can significantly improve motor skills and procedural accuracy, making AR/VR-based education superior to traditional methods in certain aspects [91]. For example, HoloAnatomy and Touch Surgery provide medical students with interactive 3D holographic anatomical models and surgical simulators, respectively, enabling realistic practice environments that directly translate to dentistry [92]. The great advantages of these systems include heightened student motivation, improved knowledge retention, and immediate feedback on performance, allowing for repeated practice without compromising patient safety [93]. For instance, the IMMPLANT VR simulator allows dental postgraduates to practice virtual implant placement within a subject-specific 3D model of a lower jaw, promoting greater spatial awareness of complex anatomy [94]. Such haptic-enabled VR simulations not only enhance tactile feedback, allowing students to "feel" virtual teeth, but also provide realistic visual and auditory cues to create a truly immersive learning experience [94,95]. This immediate feedback mechanism, coupled with the opportunity for self-assessment, empowers students to refine their techniques and critical decision-making skills independently [96,97].

3.13. Ethical Considerations

Ethical considerations and practical challenges of the use of AI in Periodontology & implantology include concerns regarding data privacy, algorithmic bias, the potential for deskilling among clinicians reliant on AI assistance, and the large initial investment required for cutting-edge technologies, coupled with their inherent technical complexities [53,98]. Furthermore, the integration of AI models, while promising for enhanced diagnostic accuracy and treatment personalization, introduces complexities in data governance and ethical oversight, particularly concerning patient confidentiality and data security [64,99]. The ethical handling of data anonymization and secure storage protocols is paramount to decrease risks associated with sensitive patient information in AI-driven systems. Clear ethical guidelines and regulations for AI use in dentistry must be developed, to ensure responsible and beneficial application and address concerns such as patient confidentiality [61,100]. Furthermore, ensuring compliance with privacy regulations like HIPAA or GDPR is crucial to safeguard sensitive patient data used in AI systems, preventing unauthorized access and misuse [75,101]. Robust regulatory frameworks are needed to govern AI's application in healthcare [75, 36,102]. These frameworks must balance innovation with patient protection, addressing issues such as data ownership, consent, and accountability for AI-driven decisions [90, 16]. A significant challenge also arises from ensuring data privacy and security, given the extensive use of sensitive patient health information in training and operating AI models [75,103]. A major limitation in current literature is the lack of standardized reporting frameworks, which complicates regulatory evaluation and clinical adoption.

3.14. Bias in AI Algorithms

The potential for algorithmic bias in AI systems necessitates rigorous validation and continuous monitoring to ensure equitable and unbiased treatment recommendations for all patient demographics [19,104] .Development and deployment of AI algorithms in dentistry must actively counteract inherent biases that could lead to disparate health outcomes among diverse patient populations, emphasizing the need for transparent and explainable AI models. This requires meticulous attention to data collection, algorithm design, and ongoing monitoring to ensure fairness and equity in diagnostic and treatment recommendations [64,105]. Dental professionals need to understand the reasoning behind AI-generated recommendations to build trust and effectively integrate these tools into their practice [64,106]. Moreover, inadequate standardization of data collection, processing, and validation methods can further exacerbate data bias, leading to AI models that are neither robust nor reproducible [17,107]. Such variability not only undermines the reliability and trustworthiness of AI solutions but also poses significant challenges for regulatory bodies tasked with ensuring the safety and efficacy of these technologies before widespread clinical adoption [59,108].

4 Future Perspectives and Research Directions

One crucial area for future exploration involves the development of hybrid intelligence models, where AI collaborates with human clinicians to leverage the strengths of both, enhancing diagnostic accuracy and treatment planning while maintaining human oversight and ethical accountability, allowing for greater transparency and interpretability in clinical decision-making [38,109]. This collaboration can also foster a continuous learning environment, where AI models are refined through real-world clinical feedback and human expertise, leading to more robust and reliable AI applications in periodontology and implantology. Further research should focus on enhancing the explainability of complex AI models, particularly deep learning algorithms, to increase clinician trust and facilitate their integration into daily practice [64,110]. Moreover, investigating the long-term impact of AI integration on patient outcomes and the cost-effectiveness of these technologies is vital for widespread adoption and policy development [22,110]. The ongoing development of real-time AI-powered surgical navigation systems, particularly those integrated with robotic surgery platforms, holds significant promise for enhancing the precision and accuracy of implant placement, enabling minimally invasive and highly precise procedures [64,111]. Future research should prioritize prospective, multicenter studies with standardized datasets and clinically relevant endpoints to improve reproducibility and facilitate regulatory approval.

5 Conclusion

Artificial intelligence shows considerable promise in periodontology and implantology; however, current evidence is predominantly derived from retrospective and experimental studies. The lack of standardized validation and limited real-world clinical data remain key barriers to widespread implementation.

Conflict of interest

The author declares that she hold no competing interests.

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