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THE ROLE OF ARTIFICIAL INTELLIGENCE IN PREDICTING AND DIAGNOSING DENTAL DISEASES: A SYSTEMATIC REVIEW

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ABSTRACT

Background: Artificial intelligence (AI) is revolutionizing modern dentistry, enhancing diagnostic accuracy, treatment planning, and patient care through machine learning (ML), deep learning, and natural language processing (NLP). AI-driven technologies, particularly convolutional neural networks (CNNs), have demonstrated remarkable performance in detecting dental diseases, automating radiographic analysis, and improving orthodontic and prosthodontic workflows. **Objectives:** This systematic review evaluates AI's role in predicting and diagnosing dental diseases, its applications in various dental specialties, and the associated challenges and ethical considerations. The review also explores future directions for AI integration in dental practice. **Methods:** A structured literature search was conducted across PubMed, Google Scholar, Scopus, IEEE Xplore, and Web of Science using a combination of controlled vocabulary (MeSH terms) and free-text keywords. Studies published from 2015 onward were included, focusing on AI applications in dental imaging, diagnostics, and patient management. PRISMA guidelines were followed to ensure systematic study selection and data extraction. **Results:** AI models have shown exceptional accuracy in dental caries detection (up to 97%), periodontal disease classification, and oral cancer diagnosis. Machine learning algorithms, including supervised and self-supervised learning techniques, have improved automated cephalometric landmark detection, orthodontic treatment planning, and implantology. AI-powered chatbots and virtual assistants have enhanced teledentistry and patient engagement, improving accessibility to dental care. However, AI involvement encounters several difficulties namely dataset biases, regulatory barriers, ethical concerns, and clinician skepticism. **Conclusion:** AI is altering dentistry by improving procedures and reducing diagnosis errors. Although AI has proven great performance in many domains, its integration needs standardized validation procedures, improved dataset variation, and clinician training to assure ethical and efficient usage. Predictive analytics, customized treatment planning, and future advancements in AI-driven robotic dentistry will help to better place AI in modern dental practice.

KEYWORDS: Artificial Intelligence, Dentistry, Machine Learning, Deep Learning, Dental Imaging, Teledentistry, AI Ethics, Dental Diagnostics.

1. INTRODUCTION

Artificial intelligence (AI) is revolutionizing healthcare by improving diagnostics, personalizing treatments, and enhancing patient management through technologies like machine learning and natural language processing. While AI shows promise in surpassing traditional methods, particularly in imaging and robotic surgery, its adoption faces challenges related to data privacy, ethics, and clinical validation. As it advances, AI is expected to further streamline healthcare processes and improve patient outcomes.[1-3]

Artificial intelligence (AI) has significantly advanced dentistry, particularly in diagnostics and treatment planning. AI-driven dental imaging systems have demonstrated exceptional precision, with some algorithms detecting radiographic carious lesions with 97.1% efficiency. Deep learning models have also been developed to classify periodontal diseases, identify vertical root fractures, reduce diagnostic errors, and improve clinical evaluations. In orthodontics, AI-based models have enhanced treatment accuracy by predicting malocclusion cases with up to 80% accuracy, enabling more personalized interventions.[4] Additionally, AI has streamlined administrative workflows in dental clinics, with virtual assistants improving patient engagement, facilitating appointment scheduling, and delivering oral health education. Predictive analytics further support early detection and intervention for oral health risks by leveraging large datasets. In implant dentistry, AI has contributed to more precise implant designs by analyzing factors such as bone density and occlusal forces.[5]

Despite its rapid advancements, several challenges continue to limit the widespread adoption of AI in dentistry. One major limitation is the restricted availability and accessibility of high-quality dental data. Effective AI model training requires large datasets, yet many dental records are fragmented, stored in non-standardized formats, or constrained by privacy concerns. Additionally, bias in AI models remains a significant issue, as the datasets used for training often lack diversity, leading to diagnostic outcomes that may not be universally applicable. Furthermore, the absence of standardized approaches and validation frameworks for AI applications in dentistry poses a major barrier, making it difficult to reliably assess the performance and accuracy of various models in clinical practice.[6]

Beyond technical challenges, ethical concerns also hinder the broader adoption of AI in dental care. Many AI-driven dental applications must comply with strict regulations regarding data security, patient consent, and medical device approval, which limits their wider implementation. Additionally, the often-complex integration with existing dental practice management systems demands significant infrastructural upgrades and extensive training for effective use. Clinician acceptance and trust in AI technologies present further barriers, as many dental practitioners are hesitant to rely on AI-driven diagnostics due to fears of job displacement and uncertainty surrounding machine learning algorithms. To ensure that AI solutions are both ethical and clinically effective in enhancing patient care, collaboration among dental practitioners, developers, and regulatory bodies is essential.[7]

Looking ahead, AI is expected to play an increasingly prominent role in dentistry, extending beyond diagnosis and treatment planning to predictive healthcare solutions. AI-driven comprehensive care systems are being developed to integrate patient data, analyze treatment histories, and generate personalized treatment recommendations. Advances in machine learning and deep learning will enhance AI's ability to detect complex patterns in oral health data, enabling earlier disease detection and more precise interventions. The integration of AI with robotic-assisted surgeries, automated prosthetic design, and orthodontic monitoring is anticipated to transform clinical operations.[8] AI-powered decision-support systems will further improve real-time clinical decision-making, offering dental practitioners' data-driven insights to optimize treatment outcomes. Additionally, AI-enabled remote monitoring and teledentistry technologies are poised to expand access to dental care through virtual consultations and remote diagnostics.[9]

This review article aims to explore the application of AI in predicting and diagnosing dental disorders, evaluating its accuracy and practical applications, while also addressing the associated challenges and ethical considerations.

2. METHODOLOGY

2.1 Literature Search Strategy

A comprehensive literature search was systematically performed across multiple databases to investigate the application of artificial intelligence (AI) in the prediction and diagnosis of dental conditions. The databases utilized included PubMed (for biomedical and healthcare-related AI research), Google Scholar (for a broad range of peer-reviewed articles), Scopus (for high-impact journal publications), and IEEE Xplore (for AI and machine learning developments in healthcare and dentistry). A combination of controlled vocabulary (MeSH terms) and free-text keywords was employed to identify the most relevant studies. Search queries integrated terms such as "Artificial Intelligence AND Dentistry," "Machine Learning AND Dental Diagnosis," "Deep Learning AND Oral Disease Detection," "AI AND Dental Caries Prediction," "AI AND Periodontal Disease Classification," "Convolutional Neural Networks (CNNs) AND Dental Imaging," "Natural Language Processing (NLP) AND Dental Records," "AI in Oral Cancer Diagnosis," and "Automated Dental Radiographic Analysis." Boolean operators (AND, OR) were systematically applied to enhance search precision and coverage. Figure 1 presents the methodological framework used to classify and organize the search strategy.

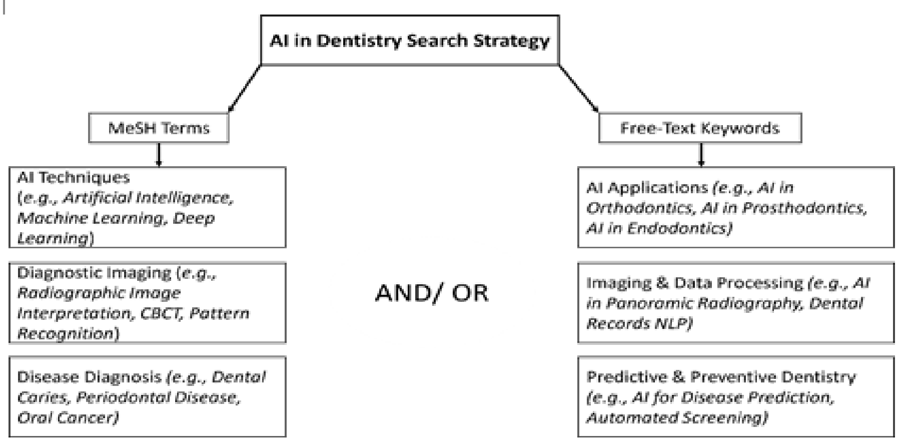


Figure 1: Structured Search Strategy for AI in Dentistry, Categorizing MeSH Terms and Free-Text Keywords.

This systematic review included only peer-reviewed articles, encompassing both systematic reviews and meta-analyses. To capture the most recent advancements in the role of AI in dentistry, only studies published from 2015 onward were considered. Selected articles specifically addressed AI applications in dental diagnostics, imaging, and disease prediction. Additionally, only articles published in English were included to maintain consistency in analysis. Conversely, non-peer-reviewed articles, editorials, opinion pieces lacking empirical evidence, and studies without a clear focus on dental-specific AI applications were excluded. Research published prior to 2015 was omitted unless it contributed fundamental insights into AI methodologies. Duplicate studies and those without full-text availability were also removed. The selected articles were evaluated according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, with quality assessment based on relevance, methodological rigor, and overall impact on the field. Figure 2 presents the detailed PRISMA flowchart illustrating the study selection process.

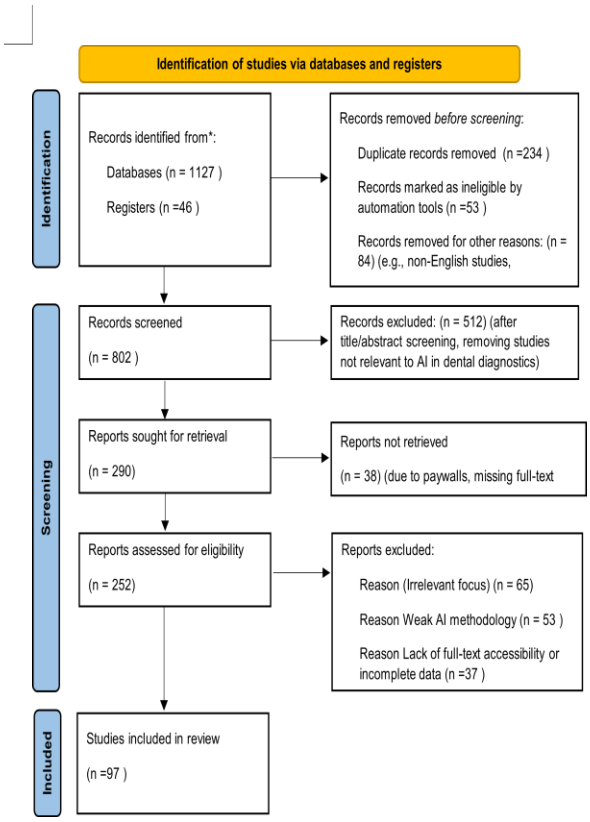


Figure 2: PRISMA Flow Diagram Showing the Study Selection Process for AI in Dentistry.

2.2 Study Selection Process

The study selection adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure a transparent and systematic process. The selection procedure comprised three main phases: identification, screening, and eligibility assessment. During the identification phase, a comprehensive search was conducted across PubMed, Google Scholar, Scopus, IEEE Xplore, and Web of Science, yielding 1,173 records. After removing duplicate entries (n = 234) and ineligible records (n = 137), 802 unique studies advanced to the screening phase. Titles and abstracts were screened for relevance to AI applications in dental diagnostics, resulting in the exclusion of 512 studies.

During the eligibility phase, full-text retrieval was attempted for 290 studies, but 38reports could not be accessed. The remaining 252 full-text articles were evaluated against predefined inclusion and exclusion criteria. Studies were excluded for irrelevant focus (n = 65), weak AI methodology (n = 53), and missing key data (n = 37). After this rigorous assessment, 97 high-quality studies were included in this systematic review. The PRISMA flow diagram (Figure 2) provides a visual representation of the study selection process.

2.3 Data Extraction and Analysis

A standardized data extraction process was implemented to ensure consistency and accuracy in evaluating the selected studies. Relevant information, including study design, AI model type, dataset size, and key performance metrics, was systematically recorded. The studies were categorized based on AI model type, distinguishing between machine learning approaches (e.g., support vector machines, decision trees), deep learning techniques (e.g., convolutional neural networks, recurrent neural networks), and natural language processing (NLP). Additionally, dataset characteristics, including the number of dental images or patient records and their sources (e.g., public repositories, hospital databases, or private clinical datasets), were documented. Studies were further classified based on their specific application areas, such as caries detection, periodontal disease classification, oral cancer diagnosis, orthodontic assessment, and endodontic imaging analysis.

To evaluate the performance of AI models, key diagnostic accuracy metrics were extracted, including accuracy (correct classification rate), sensitivity (recall, the ability to detect positive cases), specificity (correct identification of negative cases), and AUC-ROC (area under the receiver operating characteristic curve, assessing overall model performance by balancing sensitivity and specificity).

3. AI Technologies in Dental Disease Diagnosis

3.1 Overview of AI in Dentistry

In the past decade, the incorporation of AI-driven models in dental practice has expanded significantly, as evidenced by a sharp increase in research papers from 2018 to 2023, reflecting the accelerated adoption of AI technology.[10] Convolutional Neural Networks (CNNs) and Artificial Neural Networks (ANNs) play indispensable roles in enhancing radiographic image analysis, enabling the accurate identification of dental abnormalities with efficiency that surpasses traditional approaches.[11] In the context of disease detection and treatment options, AI has demonstrated high accuracy. For example, studies indicate that AI-driven models can detect dental caries with 97% accuracy, while deep learning algorithms predict malocclusion instances with an 80% success rate. Furthermore, AI-led cephalometric analysis has automatically located landmark spots with up to 95% accuracy.[12] Additionally, machine learning algorithms have been shown to assist in the categorization of periodontal disease, early detection of oral cancer, and implantology.[11, 13] In terms of caries detection, several studies have demonstrated that AI-powered models outperform traditional diagnostic methods. Schwendicke and colleagues investigated AI performance in the detection of proximal caries using a U-Net convolutional neural network (CNN). Their findings reported higher accuracy than conventional techniques accuracy (0.80) using CNN model compared to dentists whose accuracy varied from 0.61 to 0.78. AI had a much superior sensitivity (0.75 vs. 0.36) in identifying early-stage caries. (Figure 3).[14] Kühnisch et al. (2021) assessed CNN-based AI models using intraoral images for caries classification. Their results show that by lowering inter-examiner variability, deep learning improves lesion detection rates, therefore guaranteeing more reliable results.[15] In further validation of these results, Schwarzmaier and coworkers reported an AI-assisted detection model trained on more than 10,000 radiographs, with an accuracy of 92.3% and exceeding traditional diagnostic methods.[16] Figure 4 illustrates the Analysis of AI's detection performance, including true positive and false positive rates.

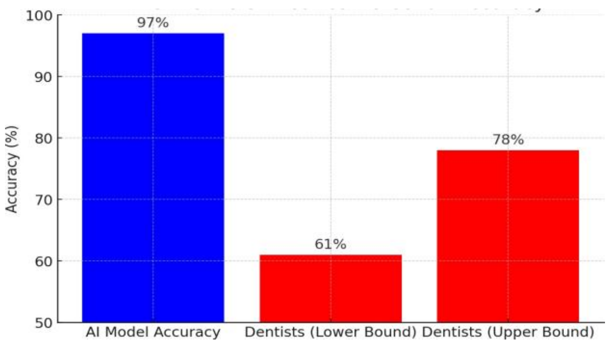


Figure 3: Comparison of AI vs. Dentists in Caries Detection Accuracy.

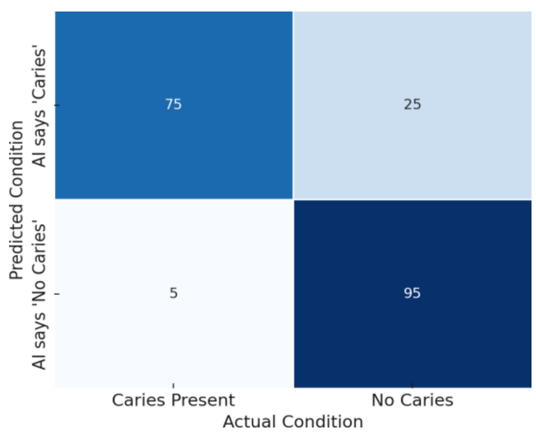


Figure 4: Confusion Matrix for AI-Based Caries Detection Performance.

In addition to conventional radiography analysis, AI models have been utilized for the early diagnosis of caries in CBCT images. A CNN-based segmentation model was evaluated, achieving a Dice similarity coefficient of 0.87.[17] Deep learning, combined with explainable AI (XAI) models, allows dentists to understand the reasoning behind AI's diagnostic results. This method enhances trust in AI-assisted processes and improves diagnostic accuracy.[18] Adnan et al. (2024) explored how AI could be employed for real-time caries diagnosis during clinical visits by analyzing intraoral images in milliseconds, providing rapid diagnostic suggestions with a 96% accuracy rate.[19]

Mertens et al. (2021) evaluated an AI-based diagnostic support tool for proximal caries diagnosis. Their findings showed that dentists using AI had significantly superior diagnostic accuracy, with an area under the receiver operating characteristic curve (AUC) of 0.89 compared to 0.85 without AI.[20] An automatic caries detection and intraoral image tooth number identification cascade R-CNN model achieved a mean average precision (mAP) score of 0.769 for caries diagnosis, with individual values ranging from 0.695 to 0.893.[21] The impact of AI assistance on dentists' gaze behavior in spotting primary proximal caries on bitewing radiographs was explored in a randomized controlled study. According to the research, AI-assisted dentists focused on pertinent image areas more quickly and for longer periods than their non-AI colleagues. AI users also demonstrated more efficient gaze patterns, focusing more on lesions and restorations and less on irrelevant visual scanning of unrelated regions. These results highlight how AI helps dental professionals optimize their diagnostic process, not just by improving accuracy but by refining the diagnostic workflow.[22]

Schwendicke et al. (2020) also investigated the economic viability of AI for proximal caries diagnosis, finding that AI-based diagnostics could reduce avoidable restorative treatments, thus lowering the cost of preventive dental care.[23] Using transfer learning and gradient-based class activation mapping (Grad-CAM), Inani et al. (2023) examined AI-enabled dental caries diagnosis. Their study evaluated five pre-trained architectures—EfficientNetV2B3, VGG19, InceptionResNetV2, Xception, and ResNet50—trained on an upgraded dental dataset. Testing accuracy for the models ranged from 93.15% to 96.58%, with VGG19 achieving the best accuracy. Notably, the ResNet50 model demonstrated a 100% validation accuracy.[24] Table 1 summarizes key studies investigating the use of AI in dental caries detection.

Table 1: Summary of Studies on AI-Based Dental Caries Detection.

Study	Method	Software/Model	Key Findings
[22]	Randomized controlled trial on dentists' gaze behavior using AI	DentalXrai Pro 1.0.4 (DentalXrai Ltd, Berlin, Germany)	Dentists using AI fixated sooner and longer on relevant image areas, improving efficiency.
[17]	External validation study for AI-based caries detection	AI-based caries detection model (unspecified web tool)	AI model achieved 92% accuracy in detecting and classifying caries using photographs.
[23]	Cost-effectiveness analysis of AI for proximal caries detection	DentalXrai Pro 1.0.4	AI increased sensitivity but led to more invasive treatments, yielding similar cost-effectiveness.
[24]	Transfer learning for AI caries detection using multiple CNN models	EfficientNetV2B3, VGG19, InceptionResNetV2, Xception, ResNet50	Transfer learning models achieved up to 96.58% accuracy in caries detection.
[16]	Validation study of AI for early childhood caries detection	Freely accessible AI-based model (web-based detection tool)	AI-based model had a 97.2% accuracy in early childhood caries detection.
[15]	CNN-based AI model for caries detection on intraoral images	Deep learning CNN model trained on 2,417 images	AI achieved 92.5% accuracy in caries detection on intraoral images.
[20]	Randomized controlled trial assessing AI for proximal caries detection	DentalXrai Pro (DentalXrai Ltd., Berlin, Germany)	AI increased dentists' sensitivity (81% vs. 72%) in proximal caries detection.
[18]	Clinical evaluation of AI-assisted caries detection using an intraoral camera	MobileNet-v3 and U-Net AI model	AI-based detection had 93.4% accuracy but showed variation across caries types.
[19]	AI-based smartphone app for decay detection on intraoral photographs	YOLOv5s and Detection Transformer	AI model achieved 90.7% precision and 85.6% sensitivity, outperforming junior dentists.
[14]	Cost-effectiveness analysis of AI in proximal caries detection	U-Net convolutional neural network	AI-assisted diagnosis was cost-effective, reducing missed lesions and treatment costs.
[21]	Cascade R-CNN for caries detection and tooth number recognition	Cascade R-CNN trained on 24,578 intraoral images	Model achieved an average precision of 0.769 for caries detection, with variation by tooth type.

Beyond diagnostics, AI has significantly impacted patient care and clinical management. AI-driven virtual dental assistants now assist with appointment scheduling, patient education, and automated follow-ups, reducing administrative burden and improving patient engagement.[13] Moreover, AI-powered telehealth solutions have enabled dentists to remotely monitor orthodontic treatments, reducing in-person visits while ensuring treatment adherence through automated assessment tools.[12,13] With the continuous advancement of AI, its role in dentistry is expected to expand further, integrating with robotic-assisted surgeries, automated prosthetic design, and AI-driven predictive analytics for preventive dentistry.[10,12] AI has also revolutionized dental radiography by enhancing image quality, segmentation, and automated diagnostics. AI-based deep learning models (such as CNNs) improve contrast and detail detection in X-rays, CBCT, and panoramic imaging, allowing for more precise diagnosis of dental diseases.[25,26] AI has been shown to increase diagnostic accuracy by up to 97% in detecting periapical pathologies and dental caries.[25]

Moreover, AI is now playing a pivotal role in predictive and personalized dentistry. AI models enable early detection of oral cancer, caries risk assessment, and periodontal disease progression by analyzing large datasets.[27,28] Using electronic dental records (EDR), artificial intelligence-powered clinical decision support (CDS) systems provide customized patient suggestions.[27] By allowing remote monitoring of orthodontic treatments and thereby lowering in-person visits by up to 33% while preserving treatment accuracy, AI-driven teledentistry is also revolutionizing dental care. Furthermore commonly used in orthodontics are AI-powered dental monitoring systems, which provide real-time evaluations and enhance patient adherence.[13]

Using deep learning models to increase diagnostic accuracy has helped AI greatly improve early oral cancer diagnosis. Deep convolutional neural networks (CNNs), including DenseNet-169 and Faster R-CNN, scored an AUC of 1.00 for oral squamous cell cancer (OSCC) diagnosis, surpassing general practitioners in classification accuracy.[29] Similarly, Devindi et al. (2024) offered a multimodal deep learning pipeline combining patient information with image analysis, hence enhancing classification accuracy over models based only on images.[30] Using a portable oral electronic endoscope, Li et al. 2024 developed an AI-based detection system with a 96% oral cancer diagnostic precision integrating U-Net and ResNet-34 models.[31] Mira et al. (2024) have suggested a smartphone-based AI system using a centered positioning technique, therefore enhancing lesion detection sensitivity by 8% and obtaining an overall accuracy of 84.3%.[32]

Oral cancer diagnosis has been much improved by recent advances in histological image processing driven by AI. Chaudhary and coworkers, Building the ORCHID database, a high-resolution histological image library meant to improve AI training for the identification of oral squamous cell carcinoma (OSCC) and oral submucous fibrosis (OSMF). This dataset provides high-quality annotated images at 1000X magnification, hence improving the classifying accuracy for deep learning models.[33] Schmidl et al. (2025) investigated the potential of AI image recognition for OSCC and leukoplakia diagnosis using ChatGPT 4.0, showing that while AI models effectively identified leukoplakia, it had difficulty with OSCC detection unless clinical history was incorporated, so improving diagnostic sensitivity from 18.2% to 100%.[34] Haq et al. (2025) obtained a remarkable 94.92% accuracy in OSCC detection using a hybrid AI technique including Gabor filtering, ResNet50 feature extraction, and CatBoost classification.[35]

The using of AI has shown great potential to improve Early oral cancer diagnosis, risk prediction, and metastasis assessment. A preliminary retrospective study explored the efficiency of deep learning in identifying oral squamous cell carcinoma (OSCC) from intraoral images and found that YOLOv5-based AI models can effectively discriminate malignant lesions with a precision of 0.667.[36] Alhazmi and colleagues concentrated on AI-driven risk prediction, in which clinical data and risk variables let an artificial neural network (ANN) model estimate oral cancer probability with an accuracy of 78.95%.[37] Emphasizing the use of deep convolutional neural networks (DCNNs) in automating the identification of pre-cancerous tongue lesions, Shamim et al. (2022) obtained almost human classification performance.[38] Finally, Ariji and coworkers showed that deep learning algorithms examining contrast- enhanced CT images could detect cervical lymph node metastases with an accuracy of 78.2%. These advancements underscore AI's growing role in early detection, diagnosis, and risk stratification in oral oncology, paving the way for more accessible and efficient cancer screening methods.[39] Table 2 provides a comprehensive summary of various studies exploring the application of AI in oral cancer detection.

Table 2. Summary of AI-Based Studies in Oral Cancer Detection.

Study	AI Model/Software	Key Findings	Limitations
[29]	DenseNet-169, Faster R-CNN	CNN models achieved AUC of 1.00 for OSCC detection, outperforming general practitioners.	Struggles with early-stage OPMD detection due to limited dataset diversity.
[30]	Multimodal Deep Learning Pipeline (ResNet-50, DenseNet-121, Inception_v3)	Multimodal AI incorporating metadata improved classification precision for early detection.	Dependent on high-quality metadata input for improved accuracy.
[31]	U-Net, ResNet-34	AI-powered detection system using oral electronic endoscope achieved 96% precision.	Initial validation showed variability in performance based on image resolution.
[33]	ORCHID Database for AI Training	ORCHID dataset improved AI classification of OSCC and OSMF with high-resolution histology images.	Limited to histology-based classification; lacks clinical image integration.
[34]	ChatGPT 4.0 Image Recognition	ChatGPT 4.0 struggled with OSCC detection but improved when clinical history was included.	Ineffective for OSCC diagnosis without added clinical context.
[32]	Deep Learning with Smartphone-Based Imaging	Smartphone-based AI approach enhanced lesion detection sensitivity by 8%, achieving 84.3% accuracy.	Dependent on high-quality image capture and positioning technique.
[36]	YOLOv5	YOLOv5 model demonstrated 0.667 precision in differentiating OSCC from intraoral images.	Moderate precision due to dataset limitations; requires further training.
[37]	Artificial Neural Network (ANN)	ANN-based risk prediction model estimated oral cancer likelihood with 78.95% accuracy.	Relatively lower specificity (60%) in distinguishing benign vs. malignant cases.
[38]	Deep Convolutional Neural Networks (DCNNs)	DCNNs achieved near-human classification performance for pre-cancerous tongue lesions.	Limited dataset size; further validation required for broader applicability.
[39]	Deep Learning CT Image Classification	Deep learning models diagnosed lymph node metastasis with 78.2% accuracy, similar to radiologists.	Not significantly better than experienced radiologists but useful as a support tool.
[35]	Gabor Filter + ResNet50 + CatBoost	Hybrid AI approach combining Gabor filtering, ResNet50 feature extraction, and CatBoost classification achieved 94.92% accuracy, outperforming traditional histopathological assessment methods.	Requires high-quality histopathology images for optimal accuracy; computationally intensive compared to conventional AI models.

AI has demonstrated exceptional accuracy in dental radiology and imaging, particularly in the analysis of panoramic, periapical, and CBCT images. A study by Nguyen et al. (2021) found that AI-based radiographic analysis improved early detection of caries, periapical lesions, and maxillofacial anomalies with an accuracy of 94.7%, outperforming traditional diagnostic methods.[40,41] Furthermore, convolutional neural networks (CNNs) have been effectively used to automate cephalometric landmark detection, thus obtaining an accuracy rate of 92.8% and greatly lowering diagnosis mistakes in orthodontic evaluation.[42,43] AI has been used to evaluate and estimate malocclusion severity. According to Cantu et al. (2020), machine learning models had an 80% success rate in estimating orthodontic treatment outcomes, therefore allowing tailored intervention planning.[44,45]

Furthermore, computerized skeletal classification and CBCT analysis driven by AI allows orthodontists to create improved treatment alternatives through orthodontic diagnosis.[42,46]

AI has demonstrated remarkable outcomes in automating periodontal disease detection and categorization. Maltez et al. (2023) indicated that AI models trained on vast periodontal data correctly achieved an accuracy of 89.3% in classification of gingival inflammation.[47,48] Moreover, quantitative methods powered by AI have been developed to improve calculus grading and plaque detection, thereby producing more objective and consistent periodontal assessments.[49–52] AI has improved periapical lesion detection and root canal morphology identification in endodontics. With a diagnostic accuracy of 96.6%, Johari and colleagues found that AI-based models could effectively identify CBCT image root fractures.[43,53,54] Algorithms for calculating working length have been used to minimize measurement errors in endodontic treatments and improve procedural accuracy.[52,55] Particularly with computer-assisted surgical planning, AI has fundamentally changed oral and maxillofacial surgery. AI-driven virtual surgical planning (VSP) approaches have improved osteotomy designs, implant placement, and orthognathic surgical techniques, therefore producing better postoperative outcomes.[56–58] Moreover, AI-driven robotic-assisted surgery is becoming an essential instrument for accurate and less invasive dental operations, decreasing surgical duration and enhancing overall efficiency.[59,60]

AI has enhanced the design and manufacturing processes of prosthetics in prosthodontics and digital dentistry. Hung et al. (2020) emphasized that AI-powered CAD/CAM software has improved prosthesis fitting accuracy, tooth shade selection, and occlusion mapping, thus drastically lowering laboratory turnaround times while increasing prosthetic standards.[42,61,62] Currently, AI-driven crown design software has shown great success in lowering design time. For instance, an in vitro study comparing AI-powered software (AI Automate and AI Dentbird Crown) with conventional CAD software found that AI models reduced the design time to one- quarter of the time required by novice CAD users (P < .01). However, despite these efficiency gains, morphological accuracy remains a challenge. AI-generated crowns exhibited significant deviations in occlusal surface accuracy compared to those designed by experienced CAD users (P < .001), and distal surface accuracy was notably lower (P = .029).[63]

Additionally, AI-based smile design applications have gained widespread adoption, enabling virtual aesthetic simulations that help in treatment planning and patient acceptance.[64] A clinical trial evaluating the Invisalign SmileView AI simulation tool demonstrated its capability to predict post-treatment smile aesthetics with high reliability, particularly in philtrum height, commissure height, smile width, buccal corridor, and smile index measurements. However, parameters such as maxillary inter-canine width and lower incisor exposure showed less predictive reliability, indicating areas where AI algorithms still require refinement.[65] AI-powered Digital Smile Design (DSD) applications, such as Smile Designer and SmileCloud, have also gained popularity. A study by Ceylan et al. (2023) compared AI-generated smile designs with those manually created by dental professionals. It found that dentists preferred manually designed smiles in most cases, while laypeople and orthodontists showed a greater acceptance of AI-generated designs, particularly in symmetric cases.[66] This suggests that AI can be an effective tool for time-saving and preliminary smile visualization, though manual refinement may still be preferred for highly detailed esthetic work.

Further studies on AI-powered smile analysis have demonstrated that machine learning algorithms can assess facial symmetry, lip position, and tooth proportions to create digital smile previews. AI-generated designs often prioritize dominant central incisors, minimal buccal corridors, and ideal tooth color, characteristics that were statistically favored by both dental professionals and patients. However, facial asymmetry remains a challenge for AI applications, as current models struggle with accurately integrating dynamic soft-tissue movements into simulations. Despite these limitations, AI-powered smile design software continues to enhance esthetic dentistry by improving communication between dentists and patients. By providing real-time visual simulations, AI helps manage patient expectations, increase treatment acceptance rates, and reduce chairside planning time. Table 3 summarizes key studies on AI applications in smile design, highlighting their findings, challenges, and future potential.[67,68]

Table 3: Summary of Key Studies on AI Applications in Smile Design.

Study	AI Application	Key Findings	Challenges	Future Potential
[65]	Invisalign SmileView AI Simulation	High accuracy in smile prediction; struggles with certain measurements.	Limited accuracy in some aesthetic parameters	AI refinement needed for dynamic smile analysis.
[66]	Digital Smile Design (DSD) applications	Orthodontists and laypeople favor AI; dentists prefer manual refinements	Manual designs still preferred for complex cases	Can improve visualization but may need manual adjustments
[67]	AI-powered smile analysis	Effective in facial symmetry and tooth proportion analysis.	Struggles with facial asymmetry integration.	Deep learning expected to enhance AI's predictive accuracy
[69]	AI-Based 3D Smile Design (REBEL software)	REBEL AI software considers patient personality and facial analysis for smile customization, improving treatment acceptance	Integration of personality-based AI design into mainstream clinical workflows is still evolving.	AI-generated customized smile designs integrating both esthetic rules and personality traits can improve patient satisfaction.
[70]	AI-Driven 3D Smile Design (REBEL/VisagSMile software)	REBEL software integrates personality and esthetic rules into digital smile design, achieving high patient satisfaction.	Esthetic expectations vary widely among patients, making fully automated smile design difficult to personalize	Enhanced AI- based digital workflows could fully personalize esthetic dentistry by integrating visual language and patient psychology

AI is also being applied in forensic dentistry, where it is used for age estimation, bite mark analysis, and human identification.[71] In forensic dentistry, gender prediction is a crucial process for identifying missing or deceased individuals. AI-based models have shown high accuracy in gender classification using panoramic dental X-ray images. Isa ATAS (2022) proposed a deep transfer learning method utilizing a pre- trained DenseNet121 model, which was trained on 24,000 panoramic dental X-ray images. Among different image resolutions tested, the 224 × 224 resolution achieved the highest accuracy of 97.25%, with teeth and mandible circumference identified as key features in gender classification.[72] Similarly, M.V. Rajee et al. (2022) introduced an automated forensic technique using a ResNet50 model, integrating a novel filter to reduce noise in dental X-ray images. Unlike Isa's approach, which relied on histogram equalization, this method improved image preprocessing and achieved an even higher accuracy of 98.17%.[73] Additionally, Goncharuk-Khomyn (2024) demonstrated that AI-driven comparative dental identification significantly improved image similarity detection in CBCT and intraoral scans, achieving an odds ratio (OR) of 1.92 (95% CI 1.26-2.14; $p < 0.05$). However, AI's role in reconstructive forensic identification remains limited, as no additional conformity benefits were observed in CBCT-based reconstructions ($p > 0.05$). These results indicate that AI is efficient but requires further confirmation for reconstructive applications.[74] Bui et al. (2023) investigated the function of AI in age estimation by the third molar maturity index (I3M). They developed a decision-making instrument that integrates deep learning with topological data analysis (TDA) to aid forensic specialists. The U-Net model had a segmentation accuracy of 91.2%, surpassing Mask R-CNN's 83.8%. The AI- generated I3M ratings had a significant association with expert evaluations, shown by a Pearson correlation value of 0.93. The AI-based approach effectively mirrored forensic expert choices in 94.7% of instances, indicating its viability for automated age estimates in forensic applications. Nonetheless, more validation on more heterogeneous datasets is necessary prior to practical deployment.[75]

Furthermore, results from a comprehensive review and meta-analysis conducted by Khan et al. (2024) confirm the considerable influence of AI on forensic odontology. The research examined 32 eligible articles and revealed that AI-driven forensic models surpassed conventional techniques in dental recognition and age prediction tasks.

The K Vaal method and Cameriere technique, when integrated with AI-driven algorithms, yielded higher accuracy levels, surpassing conventional manual approaches.[76] Table 4 summarizes key studies on AI applications in forensic dentistry. Meanwhile, Figure 5 presents a visual representation of AI's role in forensic odontology.

Table 4: Summary of AI Applications in Forensic Dentistry.				
Study	**AI Model Used**	**Application**	**Performance/Accuracy**	**Key Findings**
[72]	DenseNet121 (Deep Transfer Learning)	Gender classification	97.25% accuracy (224×224 resolution)	Teeth and mandible circumference identified as key discriminative features.
[73]	ResNet50 + Noise Reduction Filter	Gender classification	98.17% accuracy	Enhanced image preprocessing improved classification accuracy.
[74]	AI-driven CBCT and intraoral scan analysis	Comparative dental identification	OR = 1.92 (95% CI: 1.26–2.14, $p < 0.05$)	AI improved image similarity detection but had limited reconstructive applicability.
[75]	U-Net, Mask R-CNN	Age estimation (Third Molar Maturity Index – I3M)	Not reported	The AI models supported segmentation and analysis of molar development stages for age estimation.

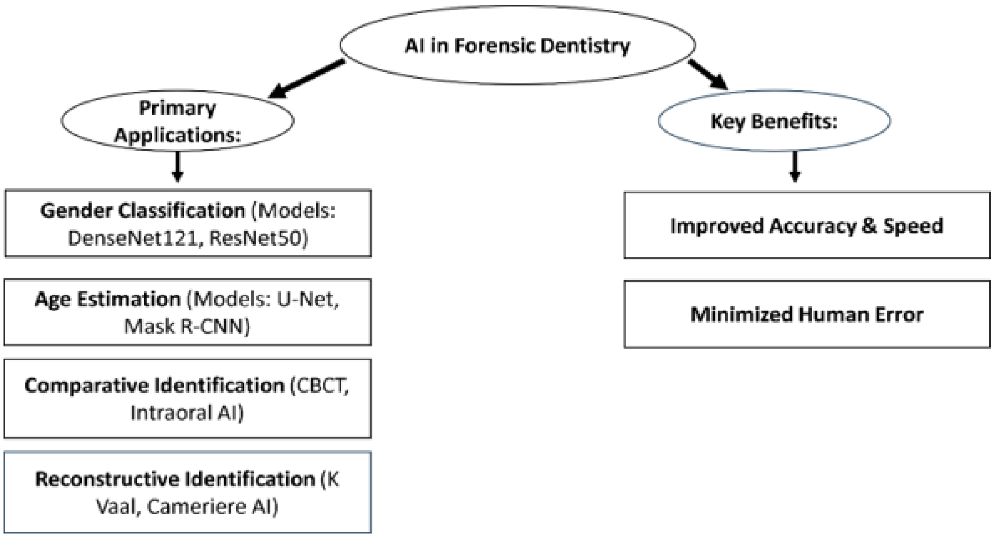


Figure 5: AI Integration in Foren3ic Denti3tr.

Another key area of AI application in dentistry is public health and teledentistry. AI has enabled population-wide oral health monitoring and remote diagnostics, particularly through AI-powered chatbots and virtual dental assistants.[77] These technologies facilitate remote screening, diagnosis, and treatment planning, reducing the burden on dental professionals and improving accessibility for underserved populations. Early oral disease identification, triaging patients, and expert referral simplification have all benefited from AI-driven teledentistry systems. Furthermore, remote monitoring systems assisted by AI have been used successfully in orthodontics and periodontal treatment. For elderly individuals, especially during the COVID-19 epidemic, the use of AI with teledentistry has been invaluable by lowering their need for physical clinic visits.[78,79]

Furthermore, teledentistry based on AI has been used to evaluate dental erosion in competitive swimmers, proving its ability to identify and prevent dental issues associated with environmental and lifestyle factors. Using AI-powered tools, a recent study remotely examined intraoral images of swimmers and reported a significant frequency of dental erosion, especially in those who spent more time in chlorinated water. This underscores AI's function in facilitating early identification and intervention in vulnerable groups via remote evaluation.[80] Hungarian dentists surveyed on AI-based teledentistry highlighted its potential in preventative care and digital patient monitoring, especially for monitoring alterations in the oral cavity over time. The survey indicated that more than 70% of participants recognized the advantages of incorporating AI-driven teledentistry into standard practice. Still, infrastructural constraints and the need for user-friendly AI interfaces were found as main obstacles to general acceptance.[81]

Moreover, telemedicine applications powered by AI have proven to be invaluable for orthodontic treatment guidance. Thurzo et al. (2021) examined an AI-based orthodontic application for treatment monitoring, demonstrating notable improvements in patient compliance after the implementation of AI-driven decision- tree algorithms. Non-tracking cases dropped among patients using the AI-enhanced technology. The study underlines how AI may preserve treatment precision and efficiency while also helping to optimize remote patient monitoring and reduce needless in-office visits.[82]

AI-based teledentistry applications are expanding their role beyond traditional diagnostics, facilitating at-home dental monitoring and preventive care. AICaries, an AI-powered smartphone application, has demonstrated significant usability in detecting early childhood caries (ECC) in underserved populations. A recent study evaluating AICaries found that 78.6% of parents successfully captured diagnostic- quality intraoral images of their children's teeth using the app. Additionally, the app achieved a system usability scale (SUS) score of 78.4, indicating high user acceptance and feasibility for real-world implementation. Parents particularly valued the app for its ability to provide immediate caries risk assessment and personalized oral health education, bridging the gap for families with limited access to dental care. However, challenges such as ensuring high-quality image capture and the need for community health worker involvement for training were identified as barriers to widespread adoption. These insights reinforce AI's potential in expanding teledentistry services while also highlighting areas that require further optimization for broader clinical integration.[83] Furthermore, AI-driven chatbots have emerged as a promising tool in remote oral health education, particularly for caregiver training in pediatric dental care. The 30-Day FunDee chatbot, designed to improve toothbrushing behaviors in young children, demonstrated effectiveness in enhancing caregiver knowledge, oral hygiene perceptions, and toothbrushing practices. The study found that caregivers using the chatbot-only intervention significantly improved their oral hygiene knowledge (P = 0.001) and toothbrushing practices (P = 0.04), even without in-person training. While in-person training combined with chatbot guidance yielded higher satisfaction scores (9.2 vs. 8.6) and greater improvements in toothbrushing frequency, the chatbot-alone model still showed notable benefits in promoting oral hygiene behaviors.[84] A detailed summary of AI applications in public health and teledentistry is presented in Table 4, outlining the key applications, findings, and challenges associated with AI-driven dental technologies.

Table 5: Summary of AI Applications in Public Health and Teledentistry.

AI Application	Key Findings	Challenges
AI-powered chatbots and virtual assistants	Facilitate remote screening, diagnosis, and treatment planning; improve accessibility.	Infrastructure limitations and need for user-friendly interfaces.
AI-driven teledentistry platforms	Help triage patients, detect oral diseases early, and streamline specialist referrals.	Requires regulatory compliance and integration into existing workflows.
AI-supported remote monitoring (orthodontics & periodontics)	Track treatment progress and adherence without frequent visits.	Limited acceptance among clinicians; further validation needed.
AI-based dental erosion assessment	AI intraoral analysis identified high prevalence of erosion in swimmers exposed to chlorinated water.	Challenges in image standardization and diagnostic accuracy.
AI in preventive care and digital patient monitoring	Over 70% of Hungarian dentists support AI for monitoring oral health changes and patient communication.	Requires further refinement for risk assessment and long-term monitoring.
AI-based orthodontic treatment coaching	AI applications improved adherence and reduced non-tracking cases, ensuring predictable outcomes.	More research needed to enhance AI's predictive capabilities.
AI-powered smartphone apps for caries detection	AICaries enabled 78.6% of parents to capture diagnostic-quality intraoral images.	Image quality dependence and need for community health worker support.
AI-driven chatbots for pediatric oral health education	The 30-Day FunDee chatbot improved caregiver knowledge and children's toothbrushing habits.	In-person training still preferred; chatbot-only models need refinement.

3.2 Machine Learning Models in Dental Diagnostics

In dental diagnostics, machine learning (ML) primarily operates through supervised and unsupervised learning methods. Supervised learning is the most widely used approach, where algorithms are trained on labeled datasets with known outputs, allowing them to learn patterns and make predictions with high accuracy.

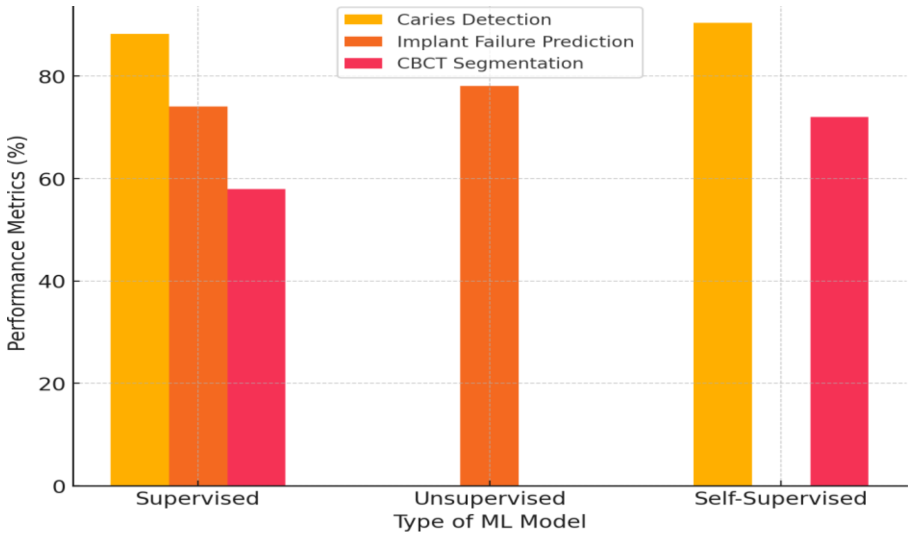
Unsupervised learning, on the other hand, analyzes unlabeled data to identify hidden patterns and clusters without predefined labels.[85] Supervised learning models have been widely used in dental radiology for caries diagnosis, periodontal disease assessment, and cephalometric landmark detection. These systems accurately identify irregularities by learning from annotated dental image databases. For periodontal bone loss, for example, convolutional neural networks (CNNs) have been used quite well.[86] Supervised deep-learning models have shown improved sensitivity and specificity in identifying maxillary sinusitis from panoramic radiographs than human observers.[85] On the other hand, unsupervised learning offers enormous potential to find new patterns in oral health data even if it is less typically applied in dental diagnosis. Early disease detection benefits from the ability of this approach to group dental radiographs depending on hidden features. Self- supervised learning (SSL) is a subclass of unsupervised learning that shows great ability to extract meaningful representations from unlabeled dental images, thus decreasing the need for human-annotated datasets. By identifying structural similarities across vast datasets, SSL-based models have been known to increase the efficiency of dental image segmentation and caries diagnosis accuracy.[87,88]

Although supervised learning is still the main method used in AI-powered dental diagnostics, unsupervised methods and hybrid approaches—such as semi- supervised learning—are under increasing investigation to use both labeled and unlabeled data, therefore strengthening the adaptability of AI applications in dentistry.[89] Deep learning-based segmentation models have lately advanced AI-driven dentistry diagnostics even further. An experimental study assessing a supervised learning model for caries detection revealed an intersection-over-union (IoU) score of 0.55 for proximal caries segmentation, thereby emphasizing the possibility for automated detection and classification of dental caries using labeled datasets. Notably, deep convolutional neural networks (CNNs) have exhibited sensitivity values between 73% and 90% and accuracy levels ranging from 76% to 88.3% in caries detection tasks.[90] Additionally, a multi-path neural network integrating both convolutional neural networks (CNNs) and clinical data has shown promise in predicting pulp exposure before caries excavation. This AI model outperformed dental students in diagnostic accuracy, achieving an F1-score of 0.71 compared to 0.58-0.61 among students. The study highlighted the potential of AI in improving preoperative assessments, particularly in cases requiring conservative interventions. However, despite AI's superior performance, the integration of AI predictions into clinical decision-making did not significantly enhance student performance, underscoring the need for further advancements in explainable AI and user adaptability in supervised learning models.[91] Furthermore, supervised learning models have been employed in tooth morphology classification, where a CNN-based model was trained on pre-scored labeled datasets to assess occlusal features and crown shape variations. The model demonstrated micro-averaged precision and recall of 0.75, macro-averaged precision of 0.73, and an AUC score of up to 0.72, confirming its effectiveness in automating morphological assessment.[92] A supervised learning-based AI system shows strong performance in automatically detecting and classifying dental restorations on panoramic radiographs. With a cubic support vector machine (SVM) with error-correcting output codes, Abdalla-Aslan et al. 2020 developed a machine-learning method to classify restorations into 11 categories. With an overall classification accuracy of 93.6%, this technique correctly recognized 94.6% of restorations. The sensitivity for identifying amalgam fillings and crowns was 100%; composite fillings and root canal treatments showed somewhat reduced rates at 83.1% and 83.2%, respectively.[93] Moreover, Dental implant failures have been predicted using supervised learning methods. Liu et al. (2018) developed a mode for implant prognosis using logistic regression (LGR), support vector machines (SVM), and decision trees (DT). With an AUC of 0.741, the Bagging + DT model showed that ensemble approaches including Bagging and AdaBoost particularly increased prediction accuracy. These findings highlight the opportunities in clinical decision assistance offered by AI-based supervised models.[94] Automated maxillary third molar impact categorization using panoramic radiographs has investigated using supervised learning models. Vollmer et al. (2022) classified impacted teeth based on Archer and Root Sinus (RS) classification systems using several pre-trained supervised learning models—VGG16, ResNet50, Inceptionv3, EfficientNet, and MobileNetV2 in addition to a custom-made CNN model and the Bag of Visual Words (BoVW) technique. With the customized CNN model obtaining an AUC of 0.902, suggesting a significant potential for automated dental classification, the research discovered that the EfficientNet and MobileNetV2 models obtained classification accuracies of up to 0.771. Though the findings were less favorable when assessing these models' prediction ability for oroantral communication (OAC), MLP and RBNN models generated AUC values of 0.59 and 0.63, respectively.[95] A retrospective observational study amid to analyze dental patient records using multiple classification algorithms, including decision trees, k-nearest neighbors (KNN), decision stumps, and artificial neural networks (ANNs). Their results showed that decision tree classifiers surpassed other models, with an accuracy of 95.65%, with KNN following at 93.43%. With accuracy rates of 75.2% and 60.01%, decision stumps and neural networks demonstrated much lower values. These findings confirm that supervised learning models—especially decision trees—predict dental diagnosis depending on organized patient data. Furthermore, their research underscored the significance of data preparation, feature selection, and balancing methodologies in enhancing model efficacy. The incorporation of supervised learning into an expert dental decision support system was examined, showcasing its capability to automate diagnostic procedures and aid clinicians in treatment planning.[96]

Recently, many studies have investigated self-supervised learning as a capable alternative to traditional supervised methods in dental AI applications. A diagnostic accuracy study suggested self-supervised learning methods to enhance label efficiency in the categorization of dental caries. Trained on 38,000 bitewing radiographs (BWRs), the model showed a 6-percentage-point sensitivity increase over traditional supervised methods. Notably, self-supervised models required significantly fewer labeled annotations to achieve comparable performance, with as few as 18 annotated images yielding a sensitivity of over 45%—a level close to human diagnostic performance.[97] In addition, supervised learning models have been effectively utilized in the classification of impacted mandibular third molars using panoramic radiographs. Kim et al. (2023) developed a WideResNet (WRN)-based supervised learning model to classify the depth of impaction, spatial relation to adjacent second molars, and the relationship with the inferior alveolar nerve canal.

High predicted accuracy was shown by the model obtaining F1 ratings of 0.87, 0.87, and 0.83 for the corresponding categorization category.[98] A diagnostic AI study used three deep learning architectures—CNN, ResNet-34, and CapsNet—utilizing a dataset of 90,388 radiographic images, including bitewings, periapicals, panoramics, and cephalometric radiographs. ResNet-34 had exceptional classification performance, with an accuracy of 99.7%, surpassing both the baseline CNN and CapsNet models.[99] Using cone-beam computed tomography (CBCT) images, deep learning-based supervised models have been used to segment the inferior alveolar nerve (IAN). A machine learning-based diagnostic study reported a Dice similarity coefficient (DSC) of 0.58 in the final iteration of model training, using a convolutional neural network (CNN) framework to automate IAN segmentation." The research also showed a substantial reduction in segmentation time from 124.8 seconds in the hand-operated method to 86.4 seconds with CNN-assisted modifications. However, exact segmentation of anatomical components shows difficulties, especially in low contrast areas requiring future AI model improvement for maximum accuracy.[100] A retrospective cohort study aimed to predict dental implant loss risk using a hybrid unsupervised clustering method in 8,513 patients. The study identified six clinical clusters, with one high-risk cluster showing significantly lower survival rates. Key risk factors included age, smoking history, implant size, implant position, and surgical approach. To aid decision-making, nomograms were developed, achieving concordance indices of 0.642–0.781, providing a visual risk assessment for implant failure. This approach enhances preoperative planning and patient risk stratification, though further validation is required.[101] Zanini and co-workers explored self-supervised learning (SSL) as a solution for enhancing dental caries classification in Cone Beam Computed Tomography (CBCT) images while addressing the scarcity of annotated datasets. The study proposed a novel pipeline integrating image processing techniques with SSL tasks to pre-train models on unlabeled data before fine-tuning on labeled datasets. ResNet-18 paired with SimCLR SSL obtained an F1- score of 88.42%, accuracy of 90.44%, and sensitivity of 86.67%, therefore exhibiting a 5.5% improvement over models trained without SSL. The study also confirmed that increasing the size of the unlabeled dataset greatly improved model performance, therefore supporting SSL's possible use in dental AI when labeled data is limited.[102] Lee and colleagues (2024) developed an SSL model known as Oral-Anatomical Knowledge-informed Semi-Supervised Learning (OAK-SSL) to boost 3D CBCT segmentation and lesion detection. This approach resolves the issue of limited labeled datasets by adding oral-anatomical information into deep learning algorithms. The OAK-SSL system has three components: converting qualitative anatomical knowledge into quantitative representations, using a knowledge-informed dual-task learning architecture, and applying a semi-supervised loss function that integrates past anatomical information. The model surpassed traditional segmentation techniques when used on real-world CBCT datasets, especially in identifying minor dental lesions. OAK-SSL offers a clinically efficient method for automated CBCT interpretation by lowering dependence on substantial amounts of manually labeled datasets.[103]

Figure 7 depicts the hierarchical framework of machine learning (ML) models in dental diagnostics. Furthermore, Figure 8 illustrates a comparative performance study of machine learning models in essential dental applications.



3.3 Deep Learning and Neural Networks

Deep learning has become an indispensable tool in dentistry, especially in image-based diagnostics. It leverages artificial neural networks (ANNs) to analyze and process complex medical images with high precision. The evolution of machine learning has led to the development of convolutional neural networks (CNNs), which are widely used in dental applications such as caries detection, periodontal disease assessment, and cephalometric landmark identification, as depicted in Figure 9. These deep learning models have demonstrated performance levels comparable to and in some cases surpassing, human specialists. However, challenges such as the need for large, standardized datasets and methodological improvements remain crucial for further advancement and clinical integration.[104,105]

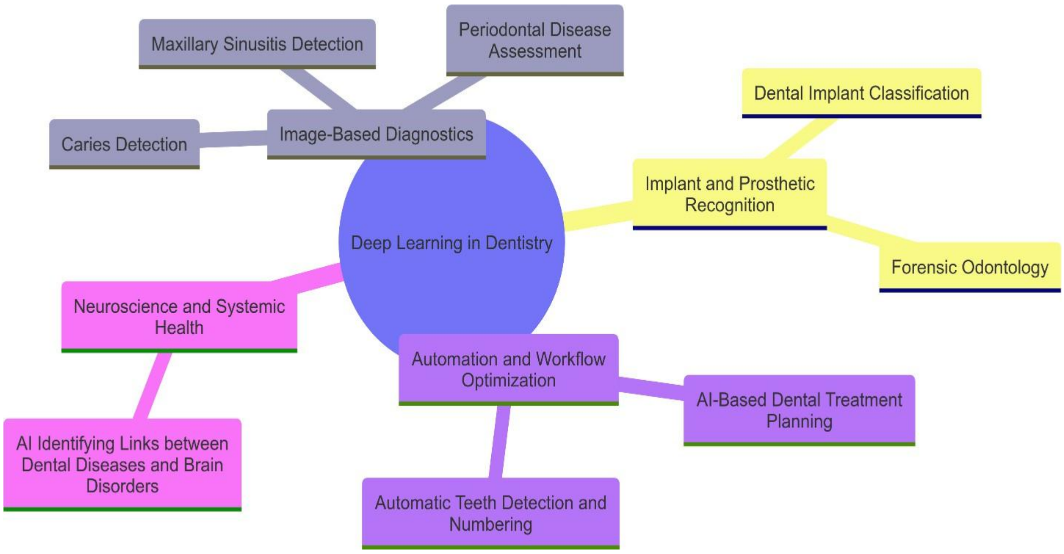


Figure 9: Overview of Deep Learning Applications in Dentistry.

Deep learning models have been increasingly utilized in dentistry to improve diagnostic accuracy and efficiency. Recent advancements in convolutional neural networks (CNNs) and deep neural networks (DNNs) have demonstrated their effectiveness in various dental applications, including implant classification, forensic odontology, and dental treatment pattern detection. For forensic dental age assessment utilizing dental panoramic radiographs, for example, deep learning models have been effectively used where InceptionV3-based networks have demonstrated great prediction accuracy.[106]

Additionally, CNN-based systems have been developed to categorize many dental implant systems from panoramic X-ray images using refined VGG16 and VGG19 models obtaining high classification performance.[107] An AI-Based Comparative Study evaluated automated deep learning models with dental specialists for implant categorization, revealing that deep learning models surpassed human experts in accuracy.[108] Moreover, approaches based on deep learning have been used for the automated identification of dental treatment patterns in forensic sciences, with EfficientDet-D3 models demonstrating great accuracy in recognizing natural teeth, prostheses, treated root canals, and implants from panoramic radiographs.[109]

Deep learning keeps transforming the diagnosis in dental field employing many neural network designs improving accuracy and efficiency. Convolutional neural networks (CNNs) have been widely used in oral and maxillofacial radiography as their superior image recognition capacity enables accurate segmentation and categorization of dental structures.[104] Deep learning has also been involved in periodontal disease detection, where CNN- based algorithms have shown notable precision in predicting periodontally compromised teeth (PCT). These models demonstrated their potential in supporting clinical decision- making by obtaining diagnostic accuracies of 81.0% for premolars and 76.7% for molars by using periapical radiography datasets.[110] Furthermore, developments in computational methods and software engineering aid in maximizing deep learning systems, therefore strengthening the adaptability of dental applications supported by artificial intelligence.

These advances point out how increasingly deep learning is playing in automating dental diagnoses and improving accuracy.[111]

Recent developments allow AI-based algorithms to precisely identify dental plaque on primary teeth, matching human experts. Using a convolutional neural network (CNN) architecture, research showed a mean intersection-over-union (MIoU) score of 0.736 for plaque identification, higher than hand evaluations by experienced pediatric dentists.[49] In periapical radiographs, where an R-CNN-based technique obtained an intersection-over- union (IoU) of 91%, deep learning models have also been used for automated tooth recognition and counting, hence enhancing efficiency and lowering human effort.[112]

Using bitewing radiographs, U-Net-based CNN models have been employed in caries diagnosis to show an F1-score of 64.14% and notably increase clinician sensitivity as a diagnostic tool. This study shows how deep learning is progressively enabling dental diagnosis to be automated.[113]

Deep learning-based models have shown incredible progress in several dental diagnostics like maxillary sinusitis diagnosis, dental disease-related brain condition identification, and caries detection. Research utilizing a convolutional neural network (CNN) model for maxillary sinusitis diagnosis on panoramic radiographs found an accuracy of 87.5%, sensitivity of 86.7%, and specificity of 88.3% relative to experienced radiologists and surpassing dental trainees.[114] Furthermore, the correlation between dental issues and brain disorders—including Alzheimer's disease—has been discovered using an intelligent bacterial optimized associative deep neural network, thereby attaining a prediction accuracy of 98.98%, considerably above previous machine learning techniques.[115] Furthermore, deep convolutional neural network (CNN) models have been applied for the detection and diagnosis of dental caries using periapical radiographs with a pre-trained GoogLeNet Inception v3 model attaining an area under the curve (AUC) of 0.917 for premolars, 0.890 for molars, and 0.845 for both, thus highlighting the efficacy of AI in improving caries diagnosis.[116]

3.4 Natural Language Processing (NLP) in Dentistry

Natural language processing (NLP) is the field of study devoted to computer-human language interaction. Dentistry is using NLP technology to enhance clinical documentation and decision-making processes as well as to facilitate patient-professional communication. NLP helps to more effectively offer healthcare by allowing the automatic analysis of textual data including patient records, clinical notes, and online reviews. These tools vary from artificial intelligence-driven chatbots helping with patient questions to automated transcription and sentiment analysis of dental data, hence lowering practitioner administrative loads. Figure 10 provides a summary of the main uses of NPL in dentistry. NLP-powered voice recognition systems can enable real-time documentation. Despite its benefits, major obstacles in the broad use of NLP in dentistry remain data privacy issues, massive, high-quality datasets, and interaction with current electronic health record (EHR) systems.[117,118] Figure 11 shows how NLP transforms unstructured clinical notes into organized outputs.

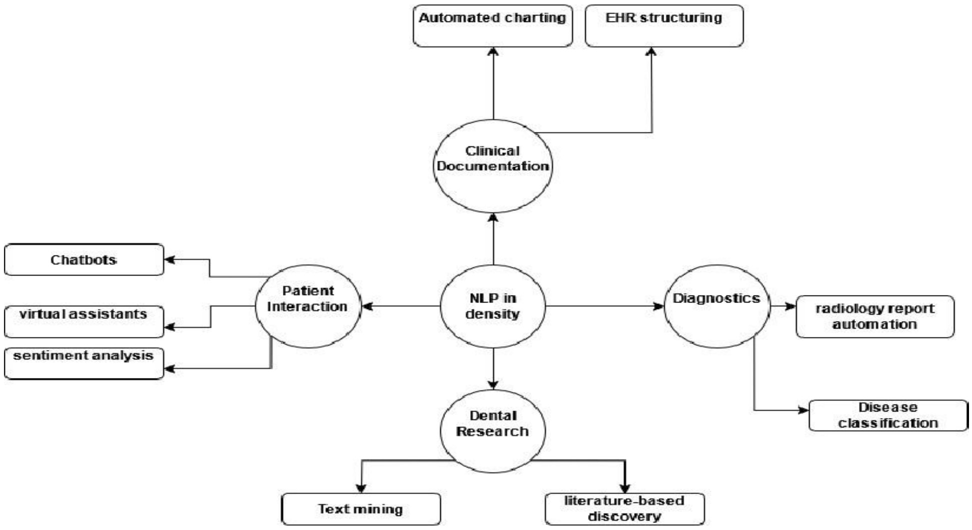


Figure 10. Overview of NLP Applications in Dentistry.

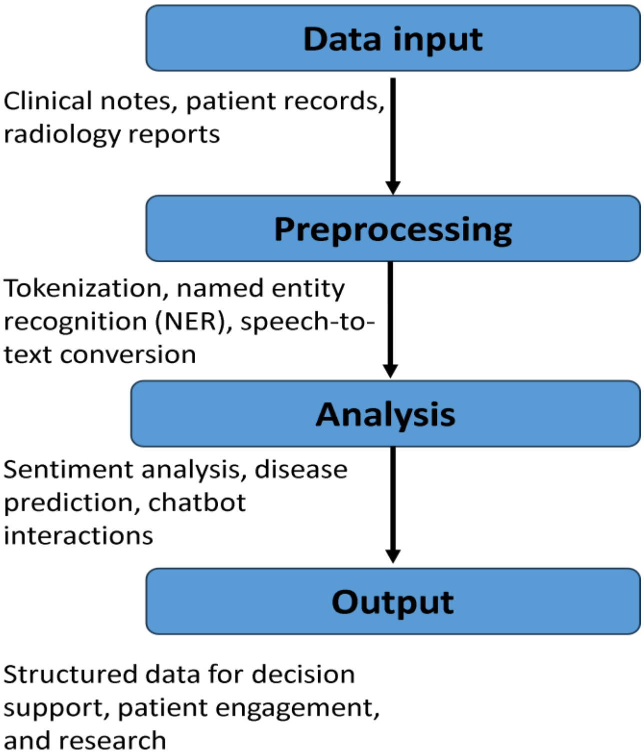


Figure 11: NLP Workflow in Dentistry – From Raw Clinical Notes to Structured Insights.

Dentistry is using NLP to automate recordkeeping, boost patient involvement, and improve clinical decision-making. NLP-driven models have been used in diagnostic contexts to extract pertinent information from unstructured clinical data, therefore supporting early identification and categorization of oral diseases. Many studies reported that NLP systems could efficiently analyze electronic health records (EHRs) to find risk variables related to periodontal disease.[119] NLP has proved to enhance dental radiology reporting By automating the extraction of important results from radiographic interpretations, thus lowering human error, and subsequently optimizing diagnosis process.[120] Beyond diagnostics, NLP tools have been used for patient-centered care. Virtual assistants and chatbots driven by AI have answered patient questions, offered oral health advice, and helped to schedule appointments.[121] has underlined how NLP-driven artificial intelligence models are used to evaluate electronic dental records (EDRs) to improve diagnosis accuracy. For instance, NLP algorithms have successfully extracted and summarized essential clinical findings from unstructured patient data, therefore decreasing the time needed for human chart checks and enhancing workflow efficiency.[122] ChatGPT and other conversational artificial intelligence systems have been investigated for their ability to provide oral health education; their responses to patient questions show remarkable accuracy. Examining ChatGPT responses revealed that while the AI model showed strong performance in clarity, relevance, and completeness, problems with bias and accuracy still exist.[123] Moreover, NLP models have been used to assess dental public health trends, thus enabling analysis of public perspectives on oral health and so informing healthcare practitioners on new challenges and educational gaps.[124]

Research indicates that dental diagnostics and patient education rely significantly on NLP models, particularly large language models such as ChatGPT. Research investigated the use of ChatGPT in the organization of electronic dental records (EDRs) for clinical decision assistance, showcasing its capacity to automate data extraction.[125,126] A study examining ChatGPT versions 3.5 and 4's accuracy and reliability, further helped to answer questions about surgical dentistry and endodontics. The results indicated that while both versions demonstrated consistent performance, their clinical usefulness is limited by the need for human monitoring because of infrequent errors and contextual restrictions.[127] A comprehensive review and meta-analysis emphasized ChatGPT's use in medical and dental research, showing its capacity to provide organized replies in clinical decision-making, teaching, and diagnostic imaging. Nonetheless, apprehensions about dependability, possible biases, and the need for further validation.[128] Comparative assessments of AI-generated material in dentistry education, including the formulation of multiple-choice questions, indicate that models such as ChatGPT and Google Bard may provide credible questions; nevertheless, human monitoring is necessary to guarantee correctness and educational validity.[129] NLP approaches have been used to analyze dental public health data, with research demonstrating their efficacy in extracting patterns from patient-generated information on digital platforms.[130] In clinical decision-making, NLP has demonstrated substantial promise, particularly in post-operative dental care, where AI-driven chatbots have been evaluated for their ability to provide clear, reliable responses to patient queries, reinforcing their role in post-procedure guidance and patient adherence.[131] Additionally, NLP has been applied to automate periodontal disease classification by analyzing EDRs, illustrating its capacity to enhance diagnostic consistency and reduce variability in clinician- recorded assessments.[132]

The integration of NLP into dentistry continues to evolve, driving advancements in diagnostics, research, and clinical efficiency. NLP pipelines have been developed to extract periodontal disease information from electronic dental records (EDRs), facilitating structured analysis of periodontitis and its links to systemic conditions such as cardiovascular disease and diabetes.[133] Similarly, NLP-based automation in dental charting has demonstrated near-human accuracy in transcribing oral examinations into structured formats, paving the way for speech-recognition-driven documentation systems.[134] Beyond clinical applications, NLP tools are enhancing dental research by processing vast biomedical literature databases, allowing researchers to uncover hidden relationships in mechanobiological networks relevant to bone and dental health.[135] The role of NLP extends to quality assessment in dentistry, where it has been utilized to automate performance tracking and treatment outcome evaluations from electronic health records.[136] In the field of dental education, NLP-powered AI models, such as ChatGPT-4o, have outperformed previous iterations in standardized assessments, demonstrating their potential as supplementary tools for dental training and examination preparation.[137]

These advancements highlight the growing impact of NLP across various domains in dentistry, improving data management, clinical workflows, and educational methodologies, while also emphasizing the need for further validation before full-scale implementation. Table 6 summarizes key studies that explore the applications of NLP in dentistry.

Table 6. Summary of Key Studies on Natural Language Processing (NLP) Applications in Dentistry.		
Key Findings	**Primary Application**	**Study**
ChatGPT is useful in academia and dental practices but does not replace professional expertise.	General AI applications in dentistry	[119]
NLP pipeline extracts periodontal disease data from EDRs, improving research and classification.	NLP in periodontal disease research	[133]
ChatGPT shows high accuracy in preventive dentistry but lower accuracy in oral surgery and cancer diagnosis.	Quality assessment of AI-generated dental information	[120]
GPT-4 performs best in Japanese dental hygienist exams, highlighting potential for educational applications.	LLM performance in dental education	[121]
NLP algorithm effectively automates dental charting, comparable in accuracy to human charting.	Automated dental charting using NLP	[134]
NLP enhances research in bone and dental mechanobiology, enabling new literature-based discoveries.	NLP in dental mechanobiology research	[135]
NLP helps extract quality measures from EHRs but requires structured data for better performance.	NLP for quality measure extraction in dentistry	[136]
ChatGPT-4o significantly outperforms 3.5 in dental exams, demonstrating improved clinical knowledge.	AI model comparison for dental examinations	[137]
AI responses improve over time, but human expertise is needed for complex clinical decision-making.	Accuracy and reliability of AI in clinical decisions	[122]
ChatGPT provides clear and accurate oral health responses but has bias concerns.	AI-driven oral health education	[123]
Deep learning-based NLP extracts structured data from Chinese EDRs, improving clinical decision support.	NLP for structuring electronic dental records	[125]
ChatGPT-4 improves diagnostic accuracy, patient interaction, and workflow efficiency in dentistry.	AI integration in dental diagnostics	[126]
ChatGPT-3.5 and 4 show comparable performance in answering dental questions with high accuracy and consistency.	AI model performance in dental education	[127]
ChatGPT and Google Bard generate dental caries-related multiple-choice questions, but human oversight is needed for quality.	AI-generated multiple-choice questions in dentistry	[129]
ChatGPT-4 provides responses similar to FDA FAQs on dental amalgam but differs in certain perspectives.	AI in dental amalgam information accuracy	[130]
LLMs aid post-operative dental care, with embedded GPT outperforming ChatGPT-3.5 in accuracy and clarity.	LLM-based chatbot applications in post-operative care	[131]
NLP methods effectively diagnose gingivitis from electronic dental records, improving classification accuracy.	NLP in automated gingivitis classification	[132]

4. Ethical, Legal, and Practical Considerations in AI Adoption

The integration of artificial intelligence (AI) in dentistry presents significant ethical concerns, particularly regarding patient autonomy, data privacy, and informed consent. AI-based systems rely on vast amounts of patient data, including electronic health records (EHRs) and radiographic images, raising concerns about data security and patient confidentiality.[138] Ethical concerns also arise from the potential biases in AI algorithms, which may result from non-representative training datasets, leading to disparities in dental diagnosis and treatment recommendations, particularly for underrepresented populations.[139] Additionally, AI's role in diagnosis raises the question of clinician reliance—whether AI should serve as an adjunct or if there is a risk of over-dependence on AI- generated recommendations (03.pdf). Maintaining transparency in AI decision-making and ensuring that AI tools are used to support, rather than replace, clinical judgment is essential to upholding ethical standards in dental practice.[140] From a legal standpoint, the use of AI in dentistry must comply with data protection laws such as the Health Insurance Portability and Accountability Act (HIPAA) in the U.S. and the General Data Protection Regulation (GDPR) in Europe.[141] These regulations establish strict guidelines on patient data handling, storage, and sharing, necessitating robust cybersecurity measures to prevent breaches. Another legal challenge involves liability—determining who is responsible when an AI- based system provides incorrect diagnoses or treatment recommendations. Clear regulatory systems help to clarify responsibility for AI errors, therefore addressing questions about possible legal consequences for dentists.[138] In addition, under constant discussion is AI's influence on dental decisions, especially in cases where its suggestions contradict those of a human doctor.

Addressing these issues depends on establishing thorough legal rules for artificial intelligence use in dentistry.[142] In dentistry, practical factors like cost, accessibility, and fit with current procedures define AI adoption. Although AI might raise diagnostic accuracy and efficiency, its use usually calls for large infrastructure, software, and training budgets.[139] Many dentists are skeptical about the dependability of AI as its usage might compromise the clinician-patient relationship by lowering direct contacts[143] Additionally, the success of AI relies on high-quality, varied datasets, which may not always be accessible in every clinical environment.[140] Ongoing education and training efforts are required to acquaint dental professionals with AI technology, therefore emphasizing its function as a supporting tool rather than a substitute for clinical knowledge to address these difficulties.[141] Along with ethical and regulatory rules, developing standardized guidelines for AI integration into dental practice will be crucial to guarantee responsible and efficient AI use in dentistry.[142]

7. Future Directions and Recommendations

Rapid developments in AI-driven research aiming at improving diagnosis accuracy, treatment planning, and patient care will define artificial intelligence (AI) in dentistry going forward. AI models are advancing to include multimodal data sources, including radiographic imaging, intraoral scans, and patient history, to enhance diagnostic results and predict disease progression with more precision. Moreover, AI-integrated robotic dentistry is advancing, with autonomous systems being designed for minimally invasive treatments, implant placement, and precision-oriented oral surgery. These robotic innovations possess the capacity to diminish human error, improve treatment uniformity, and maximize chairside efficiency. As AI advances, its use in real-time clinical decision support systems and automated treatment planning will enhance dental processes, hence enhancing patient care and accessibility.

Despite advancements in AI within dentistry, several deficiencies need rectification to improve its dependability and acceptability. A significant difficulty is the need for broad training datasets, since several existing AI models are trained on region-specific data that may not generalize well across other populations. Promoting inclusion in AI model training will mitigate bias in dental diagnostics and provide more equal healthcare solutions. The integration of AI-assisted robotic surgery in dental procedures presents a promising opportunity to revolutionize oral and maxillofacial surgery via enhanced precision and automation. Moreover, AI's participation in drug development for oral health treatments presents new opportunities for developing revolutionary therapeutic solutions for periodontal disease, dental caries, and oral cancers. AI-driven computational models may assess biochemical interactions and genetic markers to accelerate the discovery of personalized therapeutic options.

For AI to be routinely used in modern dental practice, seamless integration and clinician training are essential. Dental clinics and institutions may include AI technology via the use of AI-driven radiographic analysis tools, digital treatment planning systems, and AI-assisted diagnostic assistants. To ensure effective deployment, training programs must be developed to educate dental practitioners on AI-driven diagnosis, treatment planning, and ethical considerations. Advocating for practical AI workshops, AI-integrated dental school curriculum, and continuous education initiatives would empower practitioners to use AI's potential while maintaining human oversight in patient care.

AI is poised to profoundly influence preventive dentistry and public health initiatives by enabling comprehensive oral health surveillance. AI-driven epidemiological tools may evaluate population-level oral health trends, identifying high-risk groups for timely intervention. Furthermore, AI-driven dental education systems may enhance patient awareness, self-care behaviors, and preventive methods by providing personalized oral health recommendations based on individual risk factors. Artificial intelligence provides opportunities for automated screening and tele-dentistry services, improving treatment accessibility for rural, disadvantaged, and elderly populations. Artificial intelligence may facilitate the early detection of dental disorders, improve triage for in-person visits, and optimize public health outreach initiatives via real-time analysis of intraoral imaging and chatbot-assisted consultations.

5. CONCLUSION

Artificial intelligence (AI) used in dentistry has demonstrated notable advances in patient care, treatment planning, and diagnosis accuracy. Particularly deep learning-based models including convolutional neural networks (CNNs) and natural language processing (NLP), AI-driven models have demonstrated remarkable success in dental disease diagnosis, radiographic analysis, and clinical decision help. Often equal or surpassing human expertise, these AI algorithms can examine large databases, precisely identify early signs of periodontal disease, tooth caries, and oral cancer. Furthermore, by providing quick responses to dental concerns and enabling appointment booking, AI- driven chatbots and virtual assistants have raised patient involvement.

Unlike traditional diagnostic techniques, intelligent offers many advantages like improved efficiency, reduced human error, and rapid analysis capability of large datasets. Conventional methods can rely on subjective assessments by clinicians, which causes diagnosis variation. On the other hand, AI systems provide objective, fact-based insights that ensure consistent and reproducible results. Still, challenges remain including the requirement for high-quality, varied datasets, moral conundrums, and legal ramifications of artificial intelligence application in clinical practice.

From diagnostics to AI-assisted robotic dentistry, individualized treatment planning, and predictive analytics for disease prevention, AI will increasingly be involved in dental healthcare as it develops. Maximizing AI's promise while reducing biases and ethical dangers depends on ongoing breakthroughs in AI model training, dataset variety, and algorithmic openness. Furthermore, regulatory systems and clinician training courses to guarantee responsible and efficient use of AI as a cooperative tool instead of a substitute for human knowledge.

AI-assisted dental therapy has bright prospects. Using community-level oral health trend monitoring, AI can not only improve preventive dentistry and public health initiatives but also increase diagnostic accuracy and process optimization. Dentistry may move toward a more efficient, accessible, patient-centered future by properly using AI's capabilities, wherein technology supports evidence-based decision-making and better patient care.

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