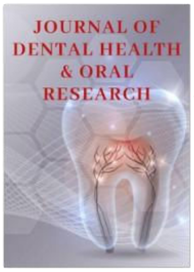

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Review Article

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Clinical Accuracy of Artificial Intelligence for Early Caries Detection in Bitewing Radiographs: A Narrative Review

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Abstract

Background: Dental caries remains one of the most prevalent chronic diseases globally, with approximately one-third of the population affected by untreated decay. Early and accurate detection is essential for timely intervention, yet conventional bitewing radiography often fails to identify incipient lesions.

Methods: The review synthesizes current literature, comparing algorithmic performance against clinician assessment and evaluating methodological limitations, implementation challenges and other considerations.

Results: AI systems demonstrate high sensitivity and diagnostic consistency, outperforming clinicians in detecting moderate lesions. However, both AI and clinicians struggle with early enamel lesions due to subtle radiographic features. Key limitations include dataset bias, interpretability issues, incomplete lesion depth characterization and potential for overdiagnosis.

Conclusions: Current evidence supports AI as a complementary diagnostic tool rather than a replacement for clinical judgment. AI enhances sensitivity and consistency but requires integration with comprehensive clinical examination, particularly for early-stage caries. Continued refinement, diverse training datasets and regulatory frameworks are needed to ensure responsible clinical implementation.

Keywords: Artificial Intelligence; Dental Caries; Bitewing Radiography; Deep Learning; Convolutional Neural Networks; Diagnostic Accuracy

Introduction

Dental Caries (DC) is considered one of the most common chronic diseases worldwide and it stands as a major concern in public health. Epidemiological studies have shown that caries in permanent teeth is the most frequent condition evaluated by the Global Burden of Disease study, which affects a large part of the world's population [1]. It is estimated that a one-third of the population in the world have untreated dental caries, which demonstrates the magnitude of the problem and its impact on oral health [1]. Dental decay is a leading cause of dental pain and tooth loss. Even though it can be prevented and treated, it continues to be a serious problem [2]. Detecting dental caries early and accurately is essential for providing treatment at the right time and in an effective way to avoid progression of the disease [2].

During the clinical examination, dental professionals rely on their knowledge and tools such as dental explorer, visual examination and dental radiographs to detect dental caries. For many years, bitewing radiographs have been the standard method to support visual and tactile caries detection because it improves the ability to identify proximal caries lesions [3]. However, despite bitewing radiographs being widely used, they sometimes fail to detect early-stage caries which is a limitation for accurate dental caries diagnosis [4]. AI can carry out tasks typically needing human intelligence. Recently, AI and deep learning, particularly through Convolutional Neural Networks (CNNs) has been successfully used to analyze medical radiographs and identify patterns that cannot be seen by the human eye [3,5]. Current research has shown that Artificial Intelligence-based systems can achieve high sensitivity, specificity and diagnostic accuracy in detecting dental caries from radiographic images. These tools have the potential to support dental professionals' clinical examination by improving diagnostic consistency and reducing variability between clinicians [3,6].

Objective

The aim of this study is to evaluate the clinical accuracy of Artificial Intelligence (AI) for early caries detection in bitewing radiographs through a narrative review of the literature.

Fundamentals of Artificial Intelligence in Dental Radiology

Artificial Intelligence in Dentistry

Artificial intelligence (AI) is a discipline in computer science concerned with creating 'machines' that can mimic the cognitive capabilities of human intelligence. Within AI, machine learning is one of the most widely used approaches in medical applications. In dental radiology, these models are trained using large collections of radiographic images that have been previously labeled by experts [7]. This process allows the algorithm to identify specific features associated with dental conditions such as caries, periodontal bone loss and periapical lesions. The idea that visual diagnosis can be improved using artificial intelligence in radiology to produce lower error rates than the human observer has ushered in an exciting era with clinical and research capabilities [8].

Principles of Artificial Intelligence

The application of AI in dental radiology involves several technical stages that allow algorithms to interpret radiographic images and identify pathological changes such as dental caries.

Technical Stages

1. *Image Acquisition:* The first step in dental image analysis is the acquisition of radiographic images. These images provide the raw data that AI algorithms analyze. Common types of dental radiographs in dental diagnostics: Bitewing, Periapical and Panoramic radiographs [7].
2. *Image Preprocessing:* Before images can be analyzed by AI algorithms, they must undergo preprocessing to improve their quality and standardize the data. It is essential because variations in image quality can significantly affect the performance of machine learning models [9]. Techniques include:

- Resizing: adjusting images to a uniform size for algorithm training
- Noise reduction: removing artifacts or distortions that may interfere with image analysis
- Contrast enhancement: improving the visibility of anatomical structures and lesions [10]

3. *Image Segmentation:* Refers to the process of dividing an image into meaningful regions that represent anatomical structures. In dental radiology, segmentation typically involves: Identification of individual teeth, Localization of dental crowns and roots, Delineation of proximal surfaces between teeth. This step allows AI systems to focus on relevant areas of the radiograph where dental caries or other abnormalities are likely to occur [8].

4. *Feature Extraction:* Once the image has been segmented, the system analyzes specific visual features that may indicate disease. Examples of extracted features include shape and morphology of dental structures, Radiolucent areas indicating potential caries lesions, texture variations within enamel and dentin and Edges and intensity patterns within the radiograph. Feature extraction enables the algorithm to differentiate between healthy tissues and pathological changes [10].

5. *Classification:* The final stage, where the AI system categorizes the analyzed regions based on learned patterns. Typical diagnostic categories include healthy tooth structure, Enamel caries, Dentin caries and Other dental abnormalities. Deep learning models such as Convolutional Neural Networks (CNNs) are commonly used for this step because of their ability to recognize complex visual patterns in medical images [11].

Machine Learning (ML), which relies on similarities and interpretation rather than specific commands, is the philosophical study of the methods used by computer systems to conduct a particular job efficiently [6]. In the practice of machine learning, a statistical model is constructed based on sample data, which is more frequently referred to as “training data”. This model is then used to teach the machine how to make judgments without being explicitly programmed to complete the work (Fig. 1) [12].

Representation Learning: This is a Machine Learning (ML) form where the machine system learns the characteristics needed for categorizing the given input. It does not need the manual categorization of information as required by machine learning (Fig. 1) [13].

Deep learning is a subcategory of ML that belongs to a bigger group of methods founded on artificial neural networks. Deep-learning frameworks have been used in various domains, including “deep neural networks, deep perception networks, recurrent neural networks and convolutional neural networks” [14]. This encompasses drug manufacturing, radiological image interpretation and histopathological condition identification, all of which have produced equivalent findings. In certain cases, superior outcomes are attained by specialists (Fig. 1) [15].

Convolutional Neural Network (CNN) is one of the most popular architectures of DL networks. The main advantage of CNN compared to its predecessors is that it automatically detects significant features of radiographic images, such as edges, contrast and densities without any human supervision which makes it the most used [16]. Recent AI advancements, particularly neural networks and deep learning, have enabled machine learning techniques for diagnosing dental caries. [17].

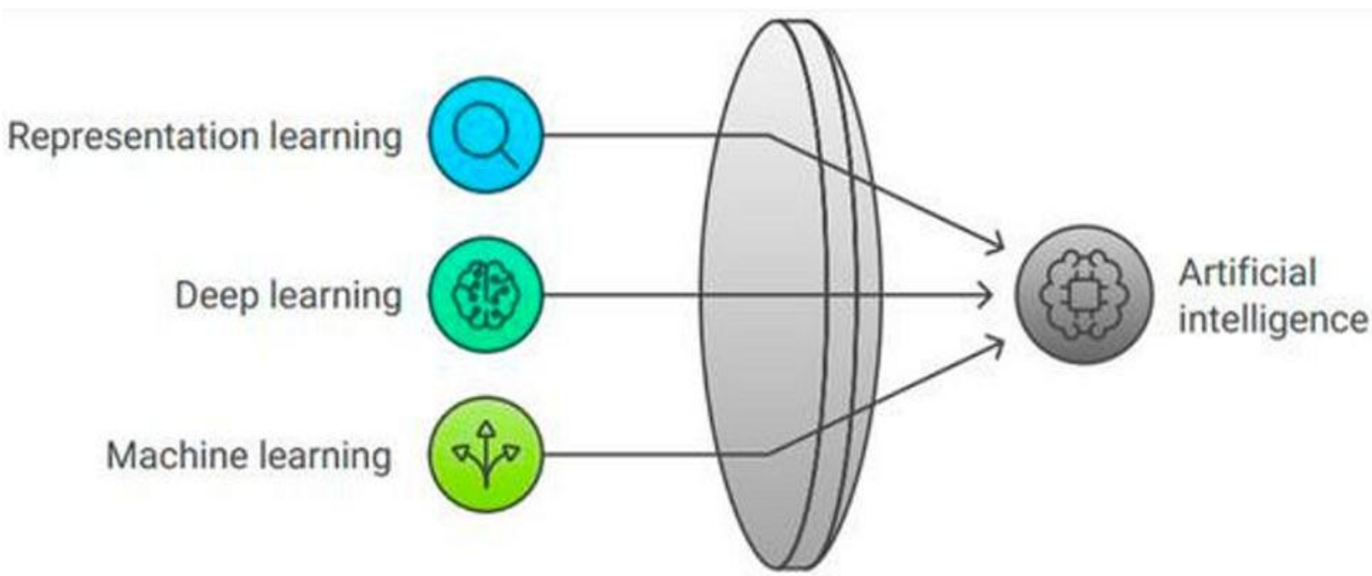

Figure 1: Relationship between machine learning, deep learning, representation learning and artificial intelligence. Adapted from the literature [6,14].

Data Processing Workflow

Through these steps, AI algorithms can automatically analyze dental radiographs and identify suspicious areas that may correspond to early caries lesions or other dental pathologies. These systems act as decision-support tools for clinicians, improving diagnostic accuracy and enabling earlier detection of oral diseases. (Fig. 2 shows an overview of the work, highlighting the key stages from image acquisition to model deployment. Each block represents a crucial step in the workflow. The following sections provide a detailed explanation of each component) [11,17].

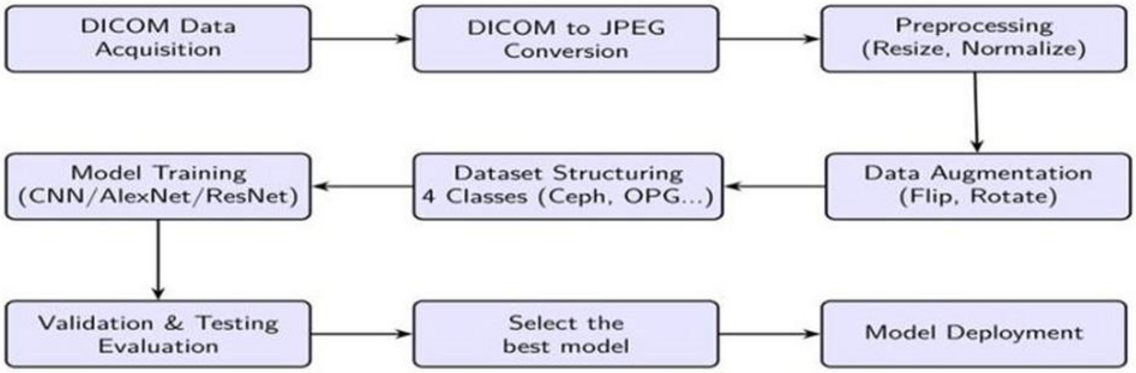

Figure 2: Overview of the data processing workflow, from DICOM image acquisition to model deployment. Adapted from the literature [11,17].

Dental Bite-Wing Radiographs

Bite-wing radiography is an intraoral technique that allows for the imaging of the crowns, roots and a portion of the alveolar bone around the maxillary and mandibular teeth simultaneously. This technique enables the simultaneous visualization and assessment of a greater number of teeth within a single image, as opposed to periapical radiographs [18]. Bitewing Radiography (BWR) has been shown to be superior to periapical or panoramic radiographs for diagnosing interproximal carious lesions, particularly in the early stages of caries formation, alveolar bone loss and calculus [19]. All types of dental caries (proximal, occlusal, root and secondary) observed on BWR were tagged, regardless of severity. In the United States, Bitewing Radiographs (BWR) is the standard of care for diagnosing interproximal carious lesions and is taught in all dental schools. Original (BWR) from Dr. Iannucci's Radiographic Caries Identification (RCI) website. Reprinted with permission [20].

Sample BWR containing segmented caries lesions from Dr. Iannucci's RCI website. According to the website, the blue area shows a moderate Interproximal Caries (IPC) lesion that extends greater than halfway through the thickness of enamel but does not involve the Dentin-Enamel Junction (DEJ). The green area depicts an advanced Intra-Cavitated Dentin Caries (ICDC) that extends to the Dentin-Enamel Junction (DEJ) or through the DEJ and into the dentin but does not extend through the dentin beyond half the distance toward the pulp. The yellow areas show severe IPC that extends through enamel, through the dentin and greater than half the distance towards the pulp. The red arrows point to radiolucent artifacts most likely caused during processing (Fig. 3,4) [20].

Figure 3: Original Bitewing Radiograph (BWR) without AI analysis. Source: Iannucci J. Radiographic Caries Identification (RCI). The Ohio State University College of Dentistry. Reprinted with permission [20].

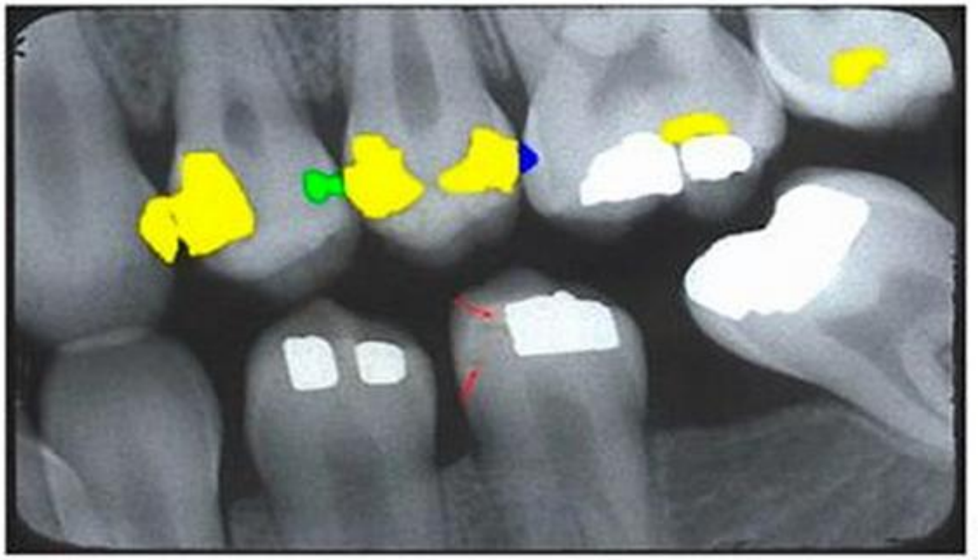

Figure 4: Bitewing radiograph with AI-assisted caries segmentation. Blue = moderate Interproximal Caries (IPC), not reaching the dentin-enamel junction (DEJ); Green = advanced IPC reaching or passing the DEJ into dentin; Yellow = severe IPC extending more than halfway toward the pulp; Red arrows = radiolucent processing artifacts. Source: Iannucci J. Radiographic Caries Identification (RCI). The Ohio State University College of Dentistry. Reprinted with permission [20].

Artificial Intelligence vs Clinicians Critical Thinking

The reviewed studies demonstrate that Artificial Intelligence (AI) systems used to diagnose interproximal carious lesions in bitewing radiographs exhibit high diagnostic performance. Overall, AI stands out for its high sensitivity and competitive overall accuracy, particularly when compared with dentists evaluating the same images [5]. In a recent comparative study, an improved YOLO-based model achieved the highest recall (0.727) and F1-score (0.687) among six dentists, suggesting superior ability to identify lesions and reduce diagnostic omissions [6]. However, some individual dentists achieved higher precision and specificity, indicating that the advantages of AI systems are not uniform across all metrics and that a noticeable tendency toward false positives persists, especially for incipient enamel lesions, as highlighted in recent assessments of YOLO-based models [23]. Evidence also indicates that algorithmic performance varies across lesion stages. AI achieves better results when lesions extend into the dentin, where radiographic features are more evident. In the same study, the model detected dentinal lesions with a precision of 0.793, recall of 0.778 and F1-score of 0.575. These findings suggest that AI is more accurate for moderate lesions-those involving superficial or middle dentin-than for incipient carious stages [21].

When compared with dentists, AI systems consistently demonstrate greater diagnostic uniformity. The algorithm applies standardized criteria when analyzing each image, unlike human evaluators, whose performance may fluctuate due to experience, workload, visual fatigue or subjective interpretation [23]. One study highlighted AI's potential to enhance diagnostic accuracy in bitewings, while another emphasized that variability among human observers remains a major limitation of conventional practice [24].

From a clinical perspective, this greater consistency is crucial because AI tends to reduce false negatives. This is particularly relevant in general dental practice, where radiographic interpretation may be affected by fatigue and attention decline during long clinical sessions. In a randomized trial, AI-assisted analysis enhanced diagnostic accuracy chiefly by improving dentists' sensitivity in detecting interproximal lesions, demonstrating that algorithmic support can help prevent diagnostic omissions [24]. However, improper use of AI outputs could also lead to more invasive treatment decisions if not interpreted with appropriate clinical judgment. Likewise, a study employing Convolutional Neural Networks (CNNs) in bitewings found that diagnostic sensitivity improved significantly when dentists used the model's recommendations [25].

Regarding lesion severity, studies suggest that AI systems markedly outperform dentists in detecting moderate lesions, particularly when radiolucency extends into superficial dentin. This is likely because such lesions exhibit well-defined radiographic characteristics, making them easier for models trained on large, annotated datasets to identify [26]. Conversely, both AI systems and dentists face challenges in detecting very early lesions, especially those confined to enamel, due to minimal demineralization, subtle radiolucency and anatomical superposition. A recent study reported that identifying early-stage lesions (RA1-RA3) remained difficult for these reasons, noting that radiographic evidence alone is insufficient for a reliable diagnosis [25].

In conclusion, current evidence supports the use of AI as an adjunct rather than a replacement for the dentist. AI serves as a complementary tool that can enhance diagnostic sensitivity, reduce interobserver variability and improve the detection of moderate lesions [26]. Nevertheless, for early-stage caries, radiographic interpretation should always be integrated with a comprehensive clinical examination and professional judgment, as even the most advanced AI systems still face limitations in detecting the earliest stages of carious lesions [27].

Current Methodological Limitations

Artificial Intelligence (AI) has shown potential accuracy in the detection of interproximal caries on bitewing radiographs, yet several methodological and practical limitations still restrict its reliability and clinical integration. A crucial limitation relates to the practical effectiveness and operational stability of AI tools [27]. For an artificial intelligence system to be accepted by clinicians, it must be affordable, intuitive to use and technically stable throughout all stages, from uploading radiographs to interpreting outputs. From a diagnostic perspective, many AI models still struggle with precise differentiation between early and moderate caries [28].

Misclassification commonly occurs at this boundary, where lesion radiolucency is slight and overlaps radiographically with normal anatomical variability. AI models frequently confuse early enamel lesions with moderate caries or fail to assess lesion depth reliably, limiting their usefulness for early detection, treatment planning and monitoring [28].

Another methodological limitation concerns incomplete lesion characterization. Previous validation studies have indicated that some AI systems do not report the depth of each detected carious lesion, which affects clinical decision-making because depth assessment is essential for determining whether noninvasive management or operative treatment is required [29]. Evidence suggests that AI may influence dentists' treatment decisions. AI assistance can increase dentists' sensitivity in detecting early enamel lesions, yet this benefit may be accompanied by a tendency toward more invasive therapy choices. This raises the methodological concern that AI tools could unintentionally shift clinical thresholds for intervention, particularly in borderline cases where early lesions are radiographically ambiguous [29,30].

Another potential limitation of AI-based caries detection relates to patient-specific factors such as age and gender. Deep learning models trained on datasets that are not demographically balanced may show reduced accuracy when applied to populations underrepresented in the training data [31].

Finally, systematic evidence suggests that AI should not be used as a single diagnostic tool for early caries detection on bitewing radiographs. AI is best positioned as a pre-screening or auxiliary technology to help rule out healthy approximal surfaces, while final diagnostic confirmation should remain with trained clinicians [32]. Overall, while AI offers substantial promise in enhancing early caries detection, its current methodological limitations, ranging from usability issues and misclassification tendencies to incomplete lesion characterization and risks of overtreatment, highlight the need for continued refinement, standardization and rigorous clinical validation [32].

Implementation Challenges and Clinical Ethics

Artificial Intelligence (AI) has increasingly been integrated into dental radiology to assist clinicians in the detection of early caries using bitewing radiographs [33]. Nevertheless, its implementation raises important ethical and legal concerns, particularly in relation to professional responsibility and patient safety [34].

One of the main challenges is the presence of bias in training datasets. AI systems depend on extensive datasets to enhance predictive accuracy. However, in dental radiology, the quantity, quality and specificity of imaging data are critical factors, since radiographic characteristics can vary substantially across patients [34].

Although many models have been shown good precision in the detection of incipient interproximal caries, most studies report a high or unclear risk of bias. This emphasizes how the quality, size and diversity of training datasets can influence the reliability of AI systems in dental radiology [35].

Another limitation associated with bitewing radiographs is that many AI systems operate as "black box" models, meaning that the decision-making process of the algorithm is not easily interpretable by clinicians [36].

Analyzing the complexity of these models, it is frequently difficult to determine how a final decision is generated or which factors have the greatest influence on the outcome. This raises ethical and responsibility challenges, especially in cases where errors could have serious consequences for the patient [37].

Other concerns include the potential for overdiagnosis due to high algorithm sensitivity and dependence of clinicians on AI recommendations. In the context of dental caries detection, where diagnostic decisions are often binary, even minor differences in the visual outputs produced by AI systems can influence clinicians' interpretations [35]. These variations may ultimately affect patient outcomes by increasing the risk of unnecessary treatments or, conversely, by contributing to missed diagnoses [33].

In addition, several technical challenges remain in the interpretation of bitewing radiographs, such as the overlap of interproximal surfaces, the difficulty in distinguishing restorative margins from carious lesions and the detection of deep lesions in areas affected by radiographic superimposition [35]. Each of these potential sources of error carries important implications for patient management and clinical decision-making [38].

Beyond the challenges associated with the use of artificial intelligence in bitewing radiographs several ethical issues have arisen that may influence its responsible implementation in clinical practice. AI systems depend on extensive datasets, which may increase the likelihood of privacy violations. In addition, the transmission and storage of these data demand strong security frameworks to safeguard patient information [39].

Privacy and data protection are major concerns in the context of artificial intelligence. The commercialization of medical data may create incentives for unethical data sharing practices. At the same time, transparency regarding how data are used and obtaining informed consent are crucial for maintaining patient trust. However, this issue becomes more complex because transparency must be balanced with the protection of intellectual property and the need to safeguard systems from potential cyber or malicious attacks [39].

Addressing the ethical limitations associated with AI development requires regulatory measures that promote transparency, inclusivity and diversity, while strengthening data privacy and ensuring accountability [38]. Such interventions may include comprehensive documentation of data sources, the use of diverse and representative datasets, robust encryption protocols and the development of clear guidelines for AI-assisted clinical decision-making. In addition, training dental professionals to adapt to AI technologies is essential to ensure the effective and responsible use of these tools in clinical practice [37].

Conclusions: Clinical Implications and Future Direction of Artificial Intelligence

Advances in technology have enabled the use of AI in medicine. In the dental field, this tool has been revolutionizing all areas of diagnosis and treatment [38]. Dentists are using it to improve medical treatment, generating faster diagnosis and analysis. To understand the future direction of artificial intelligence for early caries detection in bitewing radiographs, we analyzed it into three categories [39].

AI clinical implications ten years ago

The early days of AI in dentistry were limited to basic applications, clinically used to support specific areas of dentistry. Such as decision-making, image recognition, treatment planning, prediction and diagnosis. In 1995, a report on one of the earliest applications of AI (RNA) to evaluate malignant lesions in the oral cavity was published. The use of an intraoral camera, such as CDA/CAM, promotes the expansion of AI by integrating its advanced capabilities to interpret illnesses and anomalies that, as humans, we cannot see [39].

AI Clinical Implications in 2026

Over the last few years, AI technology has advanced and its use has become an essential part of our daily clinical life. Promoting the most accessible treatment to the patient. The doctor aims to reduce errors while increasing patient comfort; this may reduce treatment time and lead to greater financial benefits [40].

Evaluation of images: AI makes evaluation easier and more precise, distinguishing acute from chronic lesions. Enable the doctor to use this result, along with his previous knowledge, to make a preliminary diagnosis of the disease and possible treatment [38]. Detection of the occlusal, between and under restoration, such as root-level decay. To distinguish the location and classification of decay, AI needs to be trained on hundreds of radiographic images to learn the different dental organs and to evaluate a healthy human tooth vs one infected with bacteria [41].

Planification of dental treatment, especially in areas such as implantology, prosthetic dentistry and orthodontics, is necessary for patients who need an organized treatment calendar. This tool made it more accessible and precise [41].

Virtual dental assistant: In modern dental clinics, the virtual assistant can assist patients and answer questions about clinic hours, treatment information, after-treatment instructions, insurance and payment. This technology supports dental analytics for radiographic images, patient history and administrative tasks [43].

Digital Dentistry analysis of images to detect bone loss, decay and malignant illnesses in the oral cavity. Every patient is unique and requires efficient, precise treatment, which requires a knowledgeable dentist and proper use of this tool [42].

Future direction of Artificial Intelligence in Dentistry

AI has been advancing steadily over the past two decades. Based on current evidence, the future direction of artificial intelligence in dentistry looks promising [42]. The integration of this tool into the dental diagnostic may significantly improve accuracy and decision-making. This innovation would continue to support dentists' clinical judgement and medical experience and would never replace them [43]. As AI continues to expand across various areas of dentistry, we will improve the effectiveness of campus-based oral health care and students' ability to implement AI for early cavity detection using radiography [44].

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Data Availability Statement

Not applicable.

Ethical Statement

The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore, was exempt.

Informed Consent Statement

Informed consent was taken for this study.

Authors' Contributions

All authors contributed equally to this paper.

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