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(REVIEW ARTICLE)

Advancing caries detection in dentistry: A narrative review of artificial intelligence applications

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Abstract

Artificial intelligence is rapidly transforming dental diagnostics, particularly in the detection of caries, offering unprecedented precision and efficiency compared to conventional methods. This review explores the evolution of AI applications in dentistry, highlighting how machine learning, deep learning, and computer vision are reshaping diagnostic processes. Traditional methods such as visual-tactile examinations and radiographic imaging, while fundamental, often suffer from limitations including human error, inconsistency, and difficulty in early detection. AI technologies address these challenges by offering consistent, fast, and highly accurate detection capabilities. Convolutional neural networks (CNNs) have demonstrated remarkable success in analyzing bitewing, periapical, and panoramic images, often outperforming human examiners in detecting early-stage carious lesions. Beyond radiographic analysis, AI-driven image segmentation enhances diagnostic precision by objectively highlighting affected regions, supporting clinicians in devising more tailored treatment strategies. Clinical applications already show that AI not only boosts diagnostic confidence but also improves patient engagement by providing visual explanations. Despite its promising potential, the field faces hurdles such as the need for large, diverse, and high-quality datasets, concerns about data privacy, and the necessity for rigorous validation across different populations. Ethical and legal considerations, particularly around accountability and explainability, further emphasize the need for clear regulatory frameworks. Emerging trends focus on explainable AI, multidisciplinary collaborations, and personalized AI solutions that integrate with electronic dental records, paving the way for more patient-specific care. Studies to date show that AI models can achieve caries detection accuracies exceeding 80%, with some nearing 99%, demonstrating the immense future promise of this technology. However, unlocking AI's full potential in dentistry will require ongoing research, validation in real-world settings, and a concerted effort between dental professionals, AI developers, and regulators to ensure that AI systems are safe, reliable, and ethically implemented to enhance patient outcomes and revolutionize dental care.

Keywords: Artificial intelligence; Dental caries; Deep learning; CNN

1. Introduction

AI is revolutionizing a number of sectors, including health care, where it is quickly emerging as a vital instrument for improving diagnosis and treatment results. AI has revolutionized dentistry, especially in the diagnosis of diseases like tooth caries. Artificial intelligence (AI) systems can handle large datasets, identify patterns, and provide very accurate results by using complex algorithms that imitate human intellect.

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Deep Learning (DL) and Machine Learning (ML), two important subdomains of AI, are particularly useful in image-based diagnostics. While DL utilizes neural networks to evaluate pictures with amazing accuracy, ML uses algorithms to find patterns and formulate predictions based on data. As these technologies may detect minor signs that are often overlooked during human exams, they have special applications for caries detection.

AI improves the consistency of diagnosis by automating processes that reduce the unpredictability and mistakes often associated with human interpretation. Additionally, it saves time, allowing medical professionals to concentrate on better patient care. As AI develops further, its use in dentistry has the potential to improve diagnostic skills while also revolutionizing patient care by guaranteeing prompt and accurate treatment actions.

Objective of the Review

The objective of this review is to assess the present use of AI (artificial intelligence) in the identification of dental caries. Due to the shortcomings of conventional detection techniques, dental caries, a prevalent oral health concern, poses substantial diagnostic problems. AI provides a revolutionary method by using cutting-edge technologies like deep learning and machine learning to improve diagnostic speed and accuracy. Through an analysis of current developments, this demonstrates how AI may effectively overcome conventional obstacles including the possibility of misdiagnosis and variations in clinical knowledge. It also points out current research and practice gaps, highlighting the need of more creativity and interdisciplinary cooperation. The study highlights the possibility of AI to alter caries detection via this investigation, opening the door to more accurate and individualized patient treatment. The goal of this thorough assessment is to stimulate further study and technical developments that tackle present issues and maximize AI's potential in dental diagnostics.

2. Discussion

2.1. Current Methods for Caries Detection

Dental diagnostics has traditionally relied on conventional techniques for identifying cavities in teeth, such as radiographic imaging and visual-tactile exams. The capacity of the doctor to identify deterioration via dental mirrors and exploration is the foundation of visual-tactile assessments. Although this method is simple and safe, the examiner's expertise and experience have a major role in how accurate the results are. Different levels of experience might result in inconsistent early caries detection, which makes prompt management challenging.

A more detailed image of dental structures is provided by radiographic imaging, especially bitewing as well as panoramic X-rays, which make it possible to identify underlying infections and interproximal caries that would not be apparent during a clinical evaluation. Radiographs have limits even if they are useful for diagnosis. Variations in picture exposure and overlapping anatomical components might cause misunderstandings that result in incorrect positives or negative. Furthermore, worries about radiation exposure, particularly in young patients, highlight the need of improved diagnostic techniques.

Despite their significance, these conventional methods often fail to detect caries in its early stages, when preventive measures might be most successful. This discrepancy emphasizes the need for new methods, such as AI-driven diagnostics, which might improve ultimate patient outcomes by increasing detection accuracy, lowering variability, and improving current techniques [1].

2.2. AI Technologies in Dentistry

Artificial intelligence (AI) techniques, such as computer vision, deep learning, and machine learning, are transforming dental diagnostics by providing reliable, precise, and efficient caries detection systems. By resolving the underlying drawbacks, these cutting-edge technologies enhance conventional techniques and provide a new standard for dental treatment [2].

Algorithms are used in machine learning (ML) to examine data, find patterns, and anticipate results. Large dental picture datasets are used to train machine learning models for caries detection, which identify early signs of deterioration. By gradually increasing their accuracy by learning from labeled data, these models help doctors identify cavities early on, when preventative actions may have the most impact.

A specific type of machine learning called deep learning (DL) uses neural networks that simulate how the human brain functions to go one step further. Convolutional neural networks, also known as CNNs, are one of the most effective DL

algorithms for image processing. CNNs can recognize subtle patterns in radiography pictures since they are built to interpret complicated visual information. The accuracy of detecting serious infections that could be missed during human interpretation is greatly increased by this feature.

Interpreting and analyzing visual input is the subject of computer vision, another area of artificial intelligence. It automates crucial processes in dentistry, including feature extraction and picture segmentation. Computer vision algorithms enhance diagnostic consistency and save practitioner labor by identifying areas of interest in intraoral pictures and radiographs. By simplifying procedures, saving time, and reducing human error, these technologies help provide patients with better treatment [3].

The use of AI techniques—ML, DL, and computer vision—to caries detection is a prime example of how technology can transform the medical field. These developments have the potential to improve patient outcomes by increasing diagnostic capabilities, decreasing diagnostic variability, and opening the door to more precise and specialized dental treatments.

3. AI Applications for Caries Detection

3.1. Radiographic Analysis

AI has shown incredible accuracy in the analysis of radiographic pictures for the purpose of detecting dental caries. Cutting-edge systems, especially those that use neural networks based on convolution (CNNs), have shown remarkable accuracy in detecting carious lesions, often surpassing human examiners in this regard. CNNs are perfect for interpreting intricate dental radiographs since they are particularly designed to handle visual data [4]. AI programs effectively analyze bitewing, periapical, as well as panoramic images to identify early-stage deterioration. An important drawback of conventional diagnostic techniques is addressed by this early detection capacity, which lowers the possibility of false positive as well as false negative. AI systems allow for prompt treatments, which are essential for stopping the course of illness and lowering treatment costs, by seeing minute indications of degradation that the human eye could miss. AI also minimizes variability brought on by variations in examiner skill by guaranteeing consistency across diagnoses. In addition to increasing speed and accuracy, image analysis automation frees up doctors to concentrate on better patient care. These benefits have made AI-driven radiography analysis a crucial component of contemporary dentistry, revolutionizing diagnostic procedures and enhancing patient outcomes by detecting cavities early and accurately.

3.1.1. Image Segmentation

One essential use of machine learning (AI) in dental care is image segmentation, especially for the diagnosis of dental cavities. In order to separate carious lesions for in-depth analysis, this approach divides dental pictures into distinct sections. AI-driven segmentation guarantees a consistent and unbiased approach, in contrast to conventional techniques that rely significantly on a clinician's experience and may provide inconsistent results. In this procedure, sophisticated algorithms like neural networks using convolution (CNNs) are essential. These AI models can detect and separate regions of interest with amazing accuracy since they have been trained on large databases of labeled dental images. This capacity is especially helpful in identifying tiny spots that can't be seen during visual-tactile or radiographic testing. AI lowers the possibility of error, diminishes inter-operator variability, and improves diagnostic precision via automating the segmentation process. Additionally, this method improves the overall level of treatment while improving clinical operations and saving dental professionals' time. Additionally, segmented pictures provide comprehensive visual information that help physicians create more specialized and successful treatments [5].
By facilitating the early and precise diagnosis of dental problems, the use of AI-driven picture segmentation in oral diagnostics not only improves caries detection but additionally improves patient outcomes.

3.1.2. Clinical Applications

AI technologies have been effectively incorporated into diagnostic processes at a number of dental clinics, improving clinical accuracy and efficiency. By offering alternative views, spotting possible problem areas in dental photos, and pointing out early indicators of caries and other oral health conditions that can be missed in conventional evaluations, artificial intelligence (AI) applications are helping practitioners. Radiographs, intraoral pictures, and other diagnostic data may be accurately analyzed by these AI systems, which are usually driven by extensive deep learning and machine learning algorithms [6]. AI boosts diagnostic certainty by providing real-time analysis and recommendations, enabling dentists to make better judgments. This lowers the possibility of incorrect diagnosis or postponed therapy in addition to improving patient outcomes. Furthermore, by graphically representing areas of concern, AI-powered diagnostic tools

encourage patient involvement and assist patients in comprehending their current state of oral health and the need of therapy. By promoting transparency and confidence between the patient and the doctor, this visual feedback promotes proactive oral health care. Dental practitioners' approach to diagnostics is being revolutionized by the clinical use of AI in dentistry, which makes it a useful tool for delivering patient-centered, accurate, and fast treatment. These technologies will probably become more widely used in dental offices as they develop, which will enhance patient outcomes and diagnostic procedures more significantly.

4. Advantages of AI in Caries Detection

AI offers a number of noteworthy benefits over conventional dental diagnosis techniques, including:

- Improved Diagnostic Accuracy: AI algorithms are able to identify minute dental abnormalities that the human eye can miss, leading to more accurate and trustworthy diagnoses. This capacity is especially important for early caries identification, since prompt action may save additional damage.
- Consistency: AI consistently generates trustworthy outcomes without uncertainty that may emerge from variations in training, interpretation, in contrast to human physicians. This lowers the possibility of mistakes and increases diagnostic consistency.
- Time and Cost-Effective: By automating processes like image processing, AI expedites the diagnosis process and saves physicians crucial time. Both patients and healthcare professionals gain from this since it improves workflow efficiency and lowers diagnostic procedure costs.

By using these benefits, AI helps provide more precise, reliable treatment, revolutionizing the field of dental diagnostics [7].

5. Challenges and Limitations

5.1. Data Issues

AI models for dental caries detection need high-quality, varied datasets for training. However, obtaining these datasets poses considerable difficulties. Data privacy is a significant problem; patient data must be administered with the utmost secret, which restricts access to useful datasets. Furthermore, annotated datasets—which need professional picture labeling—are sometimes hard to find and costly to assemble. The creation of strong AI models that can generalize across a range of populations is hampered by the absence of enough annotated data. Since AI systems need vast amounts of high-quality information to be accurate and reliable, these constraints help to hold down advancement in the field [8]. Improving the overall efficacy of caries detection and developing AI in dental diagnosis depend on resolving these data-related issues.

5.2. Validation

Validation is a major obstacle in AI-driven caries detection. It may be difficult for AI models that were trained on certain datasets to generalize to a variety of patient populations. When used on patients from diverse age groups or ethnic backgrounds, for instance, a model that had been developed on data from a single location or demography could not function as effectively. This problem occurs since AI systems often pick up patterns specific to their initial training data, which makes it harder for them to adjust to changes in oral morphology or imaging settings. Thorough validation across a range of populations is necessary to solve this [9]. AI models' accuracy and dependability may be improved by testing them on a variety of datasets, which will increase their use and effectiveness in actual clinical situations. For AI to be widely used in dental diagnosis, this procedure is essential.

5.3. Integration

AI integration into healthcare operations requires a large infrastructure and training investment. In order to successfully utilize AI tools, dental clinics must embrace new technology and make sure that their employees are properly instructed. The complete incorporation of AI into routine dental diagnostics may be delayed by these initial expenses and the demand for continuous training, which might be a barrier to general adoption, especially in smaller or limited resources clinics [9,10].

6. Ethical and Legal Considerations

Among the most important ethical and legal issues raised by AI-driven diagnoses, especially in dentistry, is responsibility for mistakes. Determining who is at fault—the AI developer, the doctor, or the healthcare provider—becomes difficult when an AI system commits a diagnostic error. This uncertainty has the potential to reduce patient trust in AI systems. Explainable artificial intelligence (XAI) emerged as a remedy for this. By revealing how algorithms arrive at decisions, XAI aims to make AI decision-making processes visible. By enabling patients and physicians to comprehend the reasoning behind AI-driven choices, this transparency contributes to the development of trust [11]. Furthermore, the regulatory environment around AI in healthcare must change. To guarantee that AI tools are thoroughly tested for safety, precision, and effectiveness prior to being used in healthcare settings, regulatory organizations must provide thorough criteria. These guidelines need to include ethical issues including patient permission, data privacy, and algorithmic bias in addition to the technical elements of AI performance. Enforcable and transparent laws will guarantee that AI technologies fulfill strict quality requirements, enhancing patient safety and protecting legal rights.

The effective and appropriate incorporation of AI into dentistry diagnosis ultimately depends on resolving ethical and legal issues via accountability systems, comprehensible artificial intelligence, and strict regulatory control. By taking these steps, patient confidence will grow, safety will be guaranteed, and AI will be able to reach its full potential in enhancing healthcare results.

7. Current Advances of AI in caries detection

Most algorithms as of now are capable of detection dental caries with an accuracy of higher than 80% and up to 98.8%. This development shows a promising future for AI application in dentistry for caries detection. Table 01 shows the current studies results in detection of caries from dental radiographs.

Table 1 Summary of current studies in detection of dental caries from radiographic images by deep learning models

author, year	Image type	Dataset size	Architecture model	Accuracy	Sensitivity/ Recall	Specificity	Precision	F1-score/ Dice Coefficient	AUC
Devito, et. al. (2008) (12)	Bitewing	160	ANNs						
Cantu, et. al. (2020) (13)	Bitewing	252	CNNs	0.80	0.75	0.83			
Geetha, et. al. (2020) (14)	Intraoral digital images	145	ANNs	0971			0.987		
Devlin, et. al. (2021) (15)	Bitewing	24	CNNs	High	0.71				
Bayraktar, et. al. (2022) (16)	Bitewing	200	CNNs	0.9459	0.7226	0.9819			0.8719
Zheng, et. al. (2021) (17)	Radiographs	127	CNNs	0.82	0.85	0.82	0.81		0.89
Lian, et. al. (2021) (18)	Panoramic	89	CNNs	0.986	0.821			0.663	
Moran, et. al. (2021) (19)	Bitewing	45	CNNs	0.733					
Mertens, et. al. (2021) (20)	Bitewing	20	CNNs		0.81				0.89

Vinayahalingam, et. al. (2021) (21)	Panoramic	100	CNNs	0.87	0.86	0.88		0.86	0.90
Lee, et. al. (2021) (22)	Bitewing	50	CNNs		0.6502		0.6329	0.6414	
Hur, et. al. (2021) (23)	Panoramic and CBCT	792	ANNs						0.88 to 0.89
De Araujo Faria, et. al (2021) (24)	Panoramic	15	ANNs	0.988					0.9869
Mao, et. al. (2021) (25)	Bitewing	83	CNNs	0.9030					

8. Future Directions

8.1. Explainable AI (XAI)

The goal of explainable AI (XAI) is to make AI decision-making procedures more visible and intelligible. XAI builds patient and professional confidence by offering transparent explanations of how AI systems make their decisions. As the procedure for making choices is transparent and comprehensible, healthcare practitioners are more comfortable using AI technologies in their practices. Patients' confidence in the technology is increased by the AI's clarity, which makes them more at ease with AI-driven diagnosis and treatment procedures [26].

8.2. Multidisciplinary Cooperation

AI developers, dental practitioners, and regulatory agencies must work together to create strong and trustworthy AI models for caries identification. This interdisciplinary approach guarantees that artificial intelligence systems are both feasible for therapeutic usage and scientifically sound. Dental specialists provide clinical insights, AI developers provide technical know-how, and regulatory agencies make sure the systems adhere to safety and quality requirements. By working together, these organizations can overcome the obstacles to the use of AI in dentistry and guarantee that the instruments created are safe and efficient for patient care [27].

8.3. Personalized AI Solutions

Future artificial intelligence systems have to be built to provide individualized treatment that takes into account each patient's unique requirements. These systems may take into account each patient's unique medical history, preferred course of treatment, and risk factors by combining AI alongside electronic dental records (EDRs). More precise diagnosis, improved outcomes for patients, and the development of individualized treatment programs that more effectively meet each patient's unique medical requirements may all result from personalized AI solutions. The advancement of precision dentistry and the improvement of general patient care depend on this individualized approach [28].

AI has shown great potential in revolutionizing the identification of dental cavities. AI overcomes the shortcomings of conventional techniques by improving diagnostic precision and coherence via the analysis of radiographic images and the segmentation of dental structures. Its capacity to provide consistent, repeatable outcomes lowers diagnostic variability and human error. AI has the power to completely transform the way that dental caries is identified and treated in clinical settings, particularly when applied to machine learning and deep learning methods. This might result in earlier measures and more successful treatment regimens [4,5,29]. AI's contribution to improved dental care is growing as research advances, creating exciting opportunities for the field's future.

8.4. Call to Action

Clinical trials and ongoing research are crucial to the development of AI in dental diagnosis. In addition to being scientifically sound, AI solutions that are useful and reliable for everyday usage will be developed through cooperation between regulatory agencies, dental professionals, and AI developers. These collaborations will guarantee that artificial intelligence solutions are adapted to clinical requirements, offering precise and effective diagnosis [1,2,30-33].

Furthermore, the credibility of AI models will be improved and their implementation in dental practices will be expanded by the validation of these models with thorough evaluation and real-world applications. Unlocking AI's full potential to transform dental care will need continued research and cooperation.

9. Conclusion

AI has the ability to significantly alter caries detection by providing more accuracy and consistency than conventional techniques. But for AI to unlock its full potential, issues like the demand for high-quality data, worries about data privacy, and ethical issues must be resolved. To produce trustworthy, clinically useful models, cooperation between AI developers, dental specialists, and regulatory agencies is crucial. These stakeholders may guarantee that AI technologies are not only efficient but also in line with moral principles and patient safety by cooperating. AI has the potential to significantly improve dental care with further study and collaboration.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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