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Up-to-date Progress and Challenges of Using Artificial Intelligence in Clinical Dentistry

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ABSTRACT

This study examines the transformative applications of artificial intelligence in the field of dentistry, highlighting its pivotal role in enhancing diagnostic accuracy, clinical decision-making, and treatment efficiency. AI technologies, particularly clinical decision support systems, leverage automated software to improve patient outcomes by facilitating precise diagnoses, treatment plans, and prognostic predictions. As demands for increased accuracy grow, AI tools are increasingly adopted across various subfields in dentistry, such as diagnostics, radiology, endodontics, periodontology, and orthodontics. This article discusses key examples of machine learning, including convolutional neural networks (CNNs) and artificial neural networks (ANNs), which have been effectively utilized for tasks like cavity detection, disease prediction, and the automation of labor-intensive procedures. Technical advancements in AI have demonstrated impressive results, such as exceeding 90% precision and recall in tooth identification and a 99% accuracy rate in diagnosing dental caries. Furthermore, the integration of deep learning methods has provided robust diagnostic capabilities in endodontics and periodontology, significantly enhancing clinical workflows and accuracy over traditional methodologies. In orthodontics, AI facilitates treatment planning and decision-making with high sensitivity and specificity, surpassing conventional techniques. The findings indicate that while AI's potential is vast, with uses extending from treatment recommendations to robotic surgery, substantial further assessment is necessary to validate the cost-effectiveness and reliability of these technologies before they are fully integrated into standard clinical practices. This study underscores the necessity for ongoing research into AI applications within dentistry, emphasizing their ability to alleviate the burdens of clinical practice while potentially revolutionizing patient care. Therefore, the integration of AI into dental applications, although not yet commonplace, bears significant promise for enhancing the efficiency and accuracy of dental care.

KEYWORDS: artificial intelligence (AI), machine learning, neural networks (NNs), digital dentistry.

1. Introduction

The advent of Artificial Intelligence has ushered in a transformative era within the field of dentistry, presenting novel opportunities to enhance both clinical practices and patient outcomes. As a branch of medical science, dentistry has traditionally relied on visual inspections and manual assessments to diagnose and treat various oral health conditions. However, the integration of AI technologies is revolutionizing these conventional methodologies by introducing sophisticated algorithms and automated systems that significantly improve diagnostic accuracy and operational efficiency [1]. Central to this transformation is the development of clinical decision support systems (CDSS), which employ advanced computational techniques to assist dental professionals in making evidence-based decisions that optimize patient care. These systems draw on vast datasets, enabling dentists to enhance the precision of diagnoses, tailor individualized treatment plans, and predict patient prognoses with an unprecedented level of accuracy [2].

AI technologies are finding applications in an array of dental procedures, ranging from routine tasks like cavity detection to complex processes involved in forensic dentistry. The promise of these innovations lies in their ability to streamline and automate traditionally labor-intensive workflows, thus alleviating the burden on dental practitioners and improving the overall patient experience. Empirical evidence supports significant improvements in diagnostic precision, disease prediction, and treatment recommendation capabilities, underscoring the potential of AI to not only augment the role of dentists but also to redefine the standards of dental practice [3]. For instance, convolutional neural networks (CNNs) and artificial neural networks (ANNs) are making landmark contributions, enabling the identification of key dental anomalies and enhancing the understanding of root canal anatomies, thereby preventing critical errors during treatment planning.

Moreover, the surge in AI deployment across various dental specialties exemplifies a broader trend of integrating innovative technologies into healthcare, fostering a paradigm shift in how oral health is approached. Nevertheless, while the potential benefits of AI in dentistry are substantial, the transition towards widespread implementation requires rigorous evaluations of cost-effectiveness, reliability, and clinical appropriateness. A careful examination of current AI applications, clinical outcomes, and the nuances of integrating these technologies into daily practice will pave the way for a more robust understanding of their benefits and limitations. This study article aims to explore the implications of AI in dentistry, emphasizing its applications across diagnostics, treatment planning, and diverse specialty areas including endodontics, periodontology, orthodontics, and oral pathology. By highlighting recent advancements and ongoing research, this article seeks to illuminate how AI is not only reshaping the landscape of dentistry but also enhancing the quality of care delivered to patients [4].

Objectives:

The main objectives of this review are:

1. To assess and categorize the current applications of artificial intelligence in clinical dentistry, including diagnostic imaging, treatment planning, and patient management.

2. To analyze the benefits of implementing AI technologies in dental practices, focusing on improvements in diagnostic accuracy, treatment efficiency, and patient outcomes.

Applications in Dentistry:

Artificial intelligence is significantly transforming traditional practices in the dental field. AI technologies are often utilized in creating automated software solutions that improve diagnostic efficiency and data management in dentistry. Specifically, clinical decision support systems act as resources that assist and guide professionals in making better-informed decisions [5]. These systems have been implemented to improve diagnostic accuracy, aid in formulating treatment plans, and assist in predicting outcomes. The rising interest in these systems is linked to their effectiveness in providing explanations and rational reasoning.

Numerous AI-driven tools are now in use to optimize and automate dental procedures that were once time-consuming. These technologies offer various valuable services, such as increased diagnostic precision, disease forecasting, and treatment suggestions, thereby alleviating the workload of dentists. Artificial intelligence finds applications across many aspects of dentistry, ranging from cavity detection to gender identification in forensic dentistry [6].

The incorporation of AI has fundamentally transformed the dental industry, streamlining the tasks of dental professionals. AI-powered clinical decision support systems primarily aim to assist healthcare providers, including doctors and nurses. A "clinical decision support system" refers to any software that processes medical data or utilizes the medical knowledge required for interpreting such data, designed to support healthcare professionals in their clinical decision-making [7]. The rise in the application and influence of AI is particularly significant across numerous sectors, including dentistry. The capacity to mimic human intelligence for executing complex forecasts and making decisions within healthcare is increasingly recognized. In dentistry, convolutional neural networks (CNNs) and artificial neural networks (ANNs) have shown various applications. Future applications of this technology have been explored concerning scheduling, patient management, medication interactions, prognostic evaluations, and robotic surgery. However, it is essential to undertake further evaluations to determine the cost-effectiveness, reliability, and appropriateness of these AI models before their full integration into standard clinical practices. AI holds the promise of transforming both the medical and dental fields by providing solutions to a range of clinical challenges, thereby easing the workload of practitioners. Despite this potential, the adoption of AI in the dental industry remains limited.

AI in Diagnostics and Radiology:

In intraoral periapical films, Chen et al. [8] employed CNNs to count and subsequently identify teeth, demonstrating exceptional model accuracy. To calculate precision and recall on a test dataset, the study focused on determining the intersection-over-union (IOU) value between the identified elements and the actual ones. The results indicated that both precision and recall metrics exceeded 90%, with the average IOU score between identified units and ground truths reaching 91%. The findings suggest that AI tools facilitated a more efficient clinical workflow by eliminating the need for manual data entry. This automation allows dentists to save time and effort by digitally inputting dental charts. In their research, Lee et al. [9] showcased the application of CNN algorithms for the detection and diagnosis of dental caries in periapical radiographs, underscoring the effectiveness of AI in this domain. The assessment precision for models focused on premolars, molars, and a combination of both was recorded at 89.0% (with a confidence interval of 80.4–93.3), 88.0% (with a confidence interval of 79.2–93.1), and 82.0% (with a confidence interval of 75.5–87.1), respectively, yielding notably impressive results. Additionally, studies utilizing deep learning models for the detection and localization of dental lesions in near-infrared transillumination (NILT) images have shown promising outcomes, as demonstrated in research conducted by Casalegno et al. [10]. Their study achieved an average IOU score of 72.7% for a five-class segmentation task, utilizing a limited dataset of 185 training samples. Moreover, the specific IOU scores for proximal and occlusal carious lesions were reported to be 49.5% and 49.0%, respectively.

Talpur et al. [11] utilized deep learning methodologies in their research to analyze dental images for diagnosing dental caries, which includes three specific types: proximal, occlusal, and root caries. They achieved a maximum accuracy of 99% using the Neural Network Backpropagation algorithm, one of the prominent deep learning techniques. In another study, Hung et al. [12] explored the application of artificial intelligence for predicting root caries and found encouraging outcomes. Among the various machine learning algorithms analyzed, the support vector machine algorithm demonstrated the best performance, attaining an accuracy of 97.1%, a precision rate of 95.1%, a sensitivity rate of 99.6%, and a specificity rate of 94.3% in accurately identifying root caries cases.

Schwendicke et al. [13] illustrated the effectiveness of AI-based models in diagnosing dental caries using NILT images, revealing a caries lesion prevalence of 41% at the tooth level. The reported sensitivity and specificity values were 0.59 (95% CI: 0.47–0.70) and 0.76 (95% CI: 0.68–0.84), respectively. Visual analysis of the model's predictions indicated that it was particularly sensitive to areas affected by caries lesions. The study's findings suggest that moderately deep CNNs possess a commendable selective ability in detecting caries lesions.

Hiraiwa et al. [14] reported on the use of CNNs for identifying single or extra roots in Cone Beam Computed Tomography (CBCT) images and panoramic radiographs of 760 mandibular first molars from 400 patients. The research involved segmenting image patches of roots from panoramic radiographs, which were then incorporated into a deep learning system. The primary objective was to assess this system's diagnostic capabilities in classifying root morphology. Their analysis of CBCT images found additional roots in 21.4% of distal roots. The deep learning system achieved a diagnostic accuracy of 86.9% in distinguishing the presence of extra roots in distal roots compared to those with a single root.

When used with panoramic dental radiographs, CNNs developed by Ekert et al. [15] were successful in detecting apical lesions (ALs). The positive predictive value (PPV) obtained was 0.49 (standard deviation = 0.10), whereas the negative predictive value (NPV) achieved was 0.93 (standard deviation = 0.03). The study found that the level of sensitivity in molars was significantly greater compared with other types of teeth, while the level of specificity was comparatively lower.

The deep learning technique was also used by Murata et al. [16] to analyze panoramic radiographs for signs of maxillary sinusitis. This system's diagnostic performance was satisfactory. The deep learning system exhibited a high level of diagnostic performance in the detection of maxillary sinusitis on panoramic radiographs, with an accuracy rate of 87.5%. Additionally, the system demonstrated a sensitivity of 86.7% and a specificity of 88.3%. When compared with the performance of seasoned radiologists, these findings were consistent with the study of Kim et al. [17].

AI in Endodontics:

Endodontists heavily depend on the interpretation of diagnostic imaging techniques, such as intraoral radiographs, cone beam computed tomography (CBCT) scans, and orthopantomography images, for effective treatment planning and diagnosis. Convolutional neural networks with multiple layers may be advantageous for analyzing X-ray images through artificial intelligence, as this technique involves simultaneously verifying adaptive image features and executing image classification, thereby removing the necessity for predefined image cues to calibrate the identification process [18]. Dentists skilled in root morphologies and root canal anatomy can perform root canal therapy without resorting to surgical approaches. AI can not only identify errors when outlining new canals but can also detect morphological irregularities.

Automated three-dimensional tooth segmentation utilizing the CNN method was conducted by Lahoud et al. [19]. They examined 433 segmentations of teeth from CBCT radiographs to establish a quick, efficient, and reliable clinical benchmark, concluding that AI operated at a comparable performance level to that of a human operator but at a significantly faster pace.

The effectiveness of lesion diagnosis and dice coefficient indices for multilabel segmentation were assessed by Zheng et al. [20], comparing a morphologically constrained Dense U-Net with established clinical image analysis methods. Their findings indicated that this innovative deep learning approach enhanced the segmentation of CBCT images and improved the precision of pathological detection, even with a limited sample size.

Vertical root fractures (VRFs) occur very rarely in teeth that have undergone endodontic treatment. However, the radiographic identification of VRFs can be challenging and may necessitate more advanced tools. Fukuda et al. [21] proposed that CNNs offer a promising approach for detecting and quantifying VRFs on panoramic radiographs. Additionally, Kositbowornchai et al. [22] implemented a probabilistic neural network design that accurately predicted whether a tooth root was healthy or had a vertical root fracture with 95.7% accuracy.

AI in Periodontology

Efforts to integrate AI into the examination of periodontal diseases have also been undertaken. Researchers specializing in periodontology and mucosal conditions have investigated the composition of saliva and oral microorganisms. Recent studies have demonstrated that neural networks (NNs) can effectively differentiate yeasts from other bacteria present in saliva [23]. Instead of pinpointing the specific species that generate inflammatory oral compounds, this approach utilizes the concentration of methyl mercaptan in oral air as an indicator of oral odor, alongside the peak areas of restriction fragment length polymorphisms (T-RF) of the 16S rRNA gene, to inform supervised machine learning techniques. Methyl mercaptan, a volatile sulfur compound associated with yeast infections in the mouth, has been categorized using T-RF frequencies and their proportions for classification purposes [24].

The models achieved high sensitivity, specificity, and accuracy for the various stages, with all metrics exceeding 0.8 [25]. Additionally, another study reported a diagnostic accuracy of 0.85, revealing no significant discrepancies in the measures of radiographic bone loss (RBL) percentages as assessed by deep learning techniques compared to examiners.

Other approaches have utilized deep learning (DL) to detect RBL, calculate the RBL% from panoramic radiographs, and to categorize the stages of periodontitis based on these images [26]. However, despite the acceptable accuracy and repeatability of these models in assessing bone levels, panoramic radiographs have limitations such as distortion, overlap, and low resolution, making them less advisable for clinical use.

AI in Orthodontics:

Numerous research studies have demonstrated that machine learning can significantly enhance the quality of orthodontic diagnosis, treatment planning, and decision-making. Compared to traditional methods, artificial intelligence offers quicker, more precise, and more objective outcomes. Specifically, convolutional neural network models have emerged as effective tools in practical clinical environments, in contrast to more traditional ML approaches. Initially, Japanese researchers employed the CNN model to identify 10 landmarks on 153 lateral cephalograms. However, the limited sample size and inherent measurement biases affected the reliability of the results [27].

To improve accuracy, Kunz et al. utilized intra-rater and inter-rater calibration to expand their dataset to 1792 distinct cephalograms for training [28]. Aside from the incisor inclination, the CNN model's predictions for the 11 angles and distances derived from these coordinates did not show any statistically significant alterations.

In predicting bone age, the maturity of cervical vertebrae is utilized to assess how much a patient's growth diverges from normal patterns [29]. Methods for age prediction incorporate vertebral bodies characterized by trapezoidal shapes and slight edge concavities [30]. The sensitivity, specificity, and accuracy of ML-based techniques for diagnosing both vertical and sagittal skeletal maturation exceed 90% [31].

The debate between orthodontic procedures involving extractions and those that do not have yet to be resolved. Dental protrusion, crowding, and jaw dysplasia are currently treated with orthodontic extraction [32]. For deciding whether or not to perform an extraction, Xie et al. proposed decision-making models based on ANNs [33]. Using backpropagation, ANN achieved a perfect score on the training set, but it could only achieve 80% on the testing set. Artificial intelligence-based algorithms have indicated that inadequate lips and lower incisor inclination are the key determinants of whether teeth should be extracted before orthodontic treatment. Artificial intelligence models, however, have only been utilized to determine whether extractions are necessary based on cephalometric results and other data.

2. Conclusion:

In conclusion, the integration of artificial intelligence in dentistry marks a transformative shift in the field, enhancing various aspects of clinical practice, diagnostics, and patient care. As demonstrated by numerous studies, AI technologies, particularly convolutional neural networks and other machine learning algorithms, have shown remarkable efficacy in improving diagnostic accuracy, streamlining workflows, and assisting dental professionals in treatment planning. From advanced imaging analysis to predicting disease outcomes and automating labor-intensive tasks, AI's applications extend across multiple specializations, including diagnostics and radiology, endodontics, periodontology, and orthodontics. The promising results and high accuracy rates reported in the studies underscore AI's potential to revolutionize conventional practices, ultimately resulting in better patient outcomes and more efficient dental care. However, the widespread incorporation of AI into routine clinical practice necessitates further research to confirm the cost-effectiveness, reliability, and ethical implications of these technologies. As the dental landscape continues to evolve, continued investment in AI development and integration will be crucial for optimizing future dental practices.

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