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The Journal of Dental Panacea

Journal homepage: https://www.jdentalpanacea.org/

Review Article

Deep learning in dental radiographic image analysis: A review

Hemalatha Shanmugam[1]*, Lavanya Airen[1], Saumya Rawat[1]

[1]Dept. of Research, Panscience Innovations, New Delhi, Delhi, India

Abstract

Radiography is an important part of providing patients with good dental care, assisting with its most vital step- identifying diseases and irregularities on a dental image. Digital dentistry is thriving thanks to the emergence of Deep learning, a subdivision of Artificial Intelligence. It has upgraded the accuracy of diagnosis and efficiency of devising the treatment plan, further cutting down human errors and reducing the overall workload of dentists. These AI models can appropriately identify anatomical structures, such as categorizing the different types of teeth, and detect abnormalities, including periapical pathologies, jaw tumors, cysts, and oral cancer lesions. Apart from diagnosis, Deep Learning (DL) algorithms can thoroughly analyze the dental radiograph images to predict the treatment plan in orthodontic and implant treatments. However, with rapidly advancing technology, dental clinicians often find it challenging to grasp deep learning concepts applied in the sector due to a lack of education and training. This paper reviews deep learning concepts and their use in various modalities of dentistry with evidence from the studies performed by professionals and submitted to multiple journals.

Keywords: Dental imaging, Dental radiography, Convolutional neural network (CNN), Deep learning, Artificial intelligence

Received: 28-03-2025; **Accepted:** 29-05-2025; **Available Online**: 25-07-2025

1. Introduction

Dental radiography is mandatory in clinically diagnosing a condition in dentistry, as the diagnosis is not based simply on visual examination and history taking.[1,2] Obtaining a dental X-ray is a crucial step in diagnosing a dental condition. Many of these can go undiagnosed without an X-ray. Similarly, many conditions might be hidden from the human eye but can be identified in the X-ray. Dental radiography, categorized into intraoral and extraoral,[3,4] may provide a complete view of facial structures, teeth, maxillary sinus, and jaw bones, thus providing an accurate diagnosis. As a result, the efficiency of making the right treatment decision and assessing the prognosis of the treatment has been influenced significantly.[5-7] Digital radiography and Cone-Beam Computed Tomography (CBCT) have gained attention since the first decade of the 21st century, laying down the foundation for Computer Aided Detection and Diagnosis (CAD).[1] They detected specific X-ray findings using algorithms based on human knowledge and experience, which required more human effort and time. However, both traditional and computer-aided diagnosis (CAD) analysis require human involvement, where the quality and accuracy of interpretations can be challenging and depend on the individual dentists' clinical experience and knowledge. Over time, the world has transitioned from traditional to digital radiography and is now shifting toward the utilization of artificial intelligence and deep learning for more accurate, automated, and efficient analysis of dental radiographs.[3] Deep learning-powered analysis of radiographs has the potential to significantly improve and speed up the interpretation of imaging data, making it easier for dentists and oral radiologists to reach a diagnosis.[4] However, while these technologies can improve the diagnostic process, they are designed solely to assist dentists and cannot replace their level of expertise. The present paper reviews the concepts of deep learning relevant to dentistry and the current applications of deep learning across various dental fields, supported by evidence from the studies performed by professionals and published in multiple journals.

*Corresponding author: Hemalatha Shanmugam
Email: hemalatha@parchaa.com

https://doi.org/ 10.18231/j.jdp.2025.018

2. Materials and Methods

To identify relevant studies, a broad search of the English-language medical literature was conducted on 03 January 2025, utilizing databases including PubMed, Ovid Medline, and Google Scholar. The search was then updated on February 22nd, 2025.

We employed a composite of keywords related to our topic: "Deep learning," "artificial intelligence," "dental radiography," and "dental imaging", and combined them using the Boolean operators "AND" and "OR" to get relevant results. Articles retrieved from the initial search were segregated for relevance based on their titles. Additionally, the search was expanded by studying the articles included in their reference lists. By utilizing a broad range of search terms across multiple databases, we aimed to minimize publication bias. However, it is important to acknowledge that some bias may still be present due to the exclusion of non-English language literature, conference proceedings, and unpublished studies.

3. Overview of Deep Learning

There has been significant confusion in understanding the difference between the terms, Artificial Intelligence and Machine Learning, which are usually used equivalently. Artificial Intelligence (AI) is trending today, but they have been around since 1955.[8,9] It refers to the machines mimicking the tasks that are normally performed by humans quickly and effectively. They do so by analyzing the data manually fed to them.[8,10,11] **Figure 1** shows the structural hierarchy of AI and relationships between each term. Machine Learning (ML) is a subset of AI in which the computer can make decisions and predictions based on predefined data algorithms. These models continually improve their accuracy through learned data.[11,12] Machine learning has already been implemented in analyzing many medical images. Artificial Neural Networks are one of the popular Machine Learning models based on the concept of an artificial neuron, which mimics human nerve cells.[8] In the term Deep learning, 'Deep' refers to a multi-layered system of networks[13] and is also known as a Convolutional Neural Network (CNN).[10] CNN encompasses 3 layers: Convolution, pooling, and completely connected layers. The pooling layers and convolution identify and extract relevant information from raw data, whereas the third layer processes the information to derive the conclusion.[13] The higher the quality of the data fed to the system, the better the output of the deep learning model. In dentistry, most of the data are found in the form of complex image formats like clinical photographs and radiographs.[9] The quality of digital radiographic data is highly variable, with low contrast and high amplitude noise posing challenges in analyzing them with accuracy.[14,15] However, the increasing demand for oral care and awareness of oral health among the population and the disparity in the clinicians' decisions have emphasized the importance of utilizing Deep learning and Artificial intelligence for treatment planning.

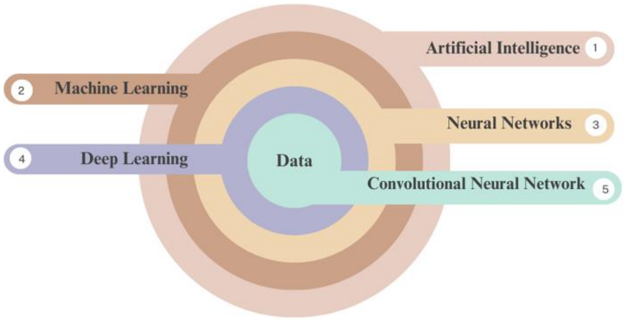

Figure 1: Artificial intelligence hierarchy: showing the structured arrangement and relationship among the different terms

4. Deep Learning in Dentistry: Applications

Deep learning models are designed to perform classification, object detection, and segmentation tasks, helping identify irregularities like tooth caries, periapical pathologies, jaw lesions, and tumors. Convolutional Neural Networks (CNNs) isolate properties from images with high accuracy, making them ideal for tasks like object classification and detection in dental radiography.[14]

For example, in a periapical radiograph showing dental caries on the right lower first molar, deep learning will be able to identify and label the carried tooth as 46 (using the Fédération Dentaire Internationale [World Dental Federation] numbering system) and then classify it as carious compared to non-carious teeth. Further, the carious region will be highlighted in a rectangular box for easy detection. Additionally, to indicate the extent of decay more precisely, the carious region is marked by different colors, a process known as segmentation, providing more detailed information and a clear view of anatomical structures.[16-18]

Deep learning models are capable of identifying key anatomical landmarks,[16-23] as well as detecting dental conditions such as caries, restorations, prosthetic treatments, dental implants,[14] periapical lesions,[16] tooth fractures,[9] jaw tumors, and odontogenic cysts[18] as described further in the article. Segmentation helps deep learning to visualize even the mandibular canal and maxillary sinus, giving a wide analysis. As a result, making a diagnosis becomes more accurate for treatment planning.[19] Popular CNN-based models used in dental applications include GoogLeNet,[4] CapsNet,[16] ResNet,[18] and You Only Look Once (YOLO) model.[15] These advanced tools support dental practitioners by enhancing image analysis, accelerating the diagnostic process, improving accuracy, and simplifying comprehensive reporting.

4.1. Dental caries

Dental caries is the most commonly encountered dental problem[20] and can have serious complications like abscess formation and swelling if left untreated. Dental Caries diagnosis is exceedingly based on a dentist's subjective visualization and subsequent radiography. Panoramic, Periapical, Bitewing radiographs, and Cone-Beam Computed Tomography (CBCT) are the different forms of radiography suggested for diagnosing dental caries based on individual cases.[9] During the evolution of deep learning, several models have been developed, including Convolutional Neural Network (CNN), Deep Neural Network (DNN), Region-Based CNN (R-CNN), Fast R-CNN, Mask R-CNN, and YOLO[20] to perform radiograph segmentation and classification tasks as described earlier. These models have been successful in diagnosing dental caries, leading to early detection and treatment planning with good prognostic results. A study in 2023 conducted by Rasool et al. investigated the accuracy of AI models in the identification and classification of dental caries in CBCT images. The deep learning model was fed with a dataset of 382 molar carious teeth and 403 non-carious molar teeth. Convolutional Neural Network then detected the presence or absence of dental decay, and the caries were classified based on their depth of tooth involvement and type of caries. The diagnostic accuracy, sensitivity, specificity, and F1 score are above 90% for both carious and non-carious molar teeth.[21] Faruk et al. conducted a study in 2022 to compare 3 Deep learning models, EfficientNet-B0, DenseNet-121, and ResNet-50, to determine which of them was able to perform the best image detection. The models used wide-angle radiographs of 562 subjects to evaluate their performance. The results showed that the ResNet-50 model obtained above 87% accuracy, sensitivity, and F1 score in caries detection compared to the others. Thus, deep learning has been proven to accurately diagnose dental caries based on image radiographs, overcoming dentist shortages in certain areas and facilitating early detection of the condition.

4.2. Orthodontics

The process of making an orthodontic diagnosis and analysis requires the use of dental radiography. Lateral cephalograms, being the cornerstone of orthodontic treatment, provide soft tissue, skeletal, and dental anatomical landmarks.[24] The lines, planes, angles, and distances between these anatomical landmarks help to generate dental measurements and to describe a patient's craniofacial morphologic features.[6] This cephalometric analysis can be accurately and efficiently performed by the use of artificial intelligence[23] and can estimate growth and development.[22] If this process were to be done manually, it would be an extremely time-consuming and error-prone process.[22,24] Hwang et al. (2021) tested this hypothesis by comparing the results of the latest AI model, YOLO, with previously published AI results and human examiners in automated cephalometric analysis. YOLO version 3 was applied for training with 1983 cephalograms and testing 200 cephalograms. The study concluded that the latest AI model was superior in performance compared to previous AI models.[25]

4.3. Tooth fracture

The third leading cause of tooth loss is either cracking or trauma, which can be prevented by early detection and treatment. However, identifying cracks can be challenging because they do not produce constant symptoms. Conventional methods like CBCT and intraoral radiographs have limited sensitivity and transparency.[26] Paniagua et al. (2018) introduced an innovative approach using high-resolution Cone Beam Computed Tomography (Hr-CBCT) scans, steerable wavelets, and machine learning techniques to detect, quantify, and locate cracked teeth. Evaluation of Hr-CBCT scans demonstrated high sensitivity and specificity.[27] Similarly, Fukuda et al. (2020) used a CNN on 330 teeth with visible fracture lines with 300 radiographs to detect vertical root fractures and found that they could serve as an effective diagnostic model for these fractures.[29] 80% of the dataset was used for training the algorithms, and 20% for testing.

4.4. Periodontal diseases

Periodontitis (the sixth most prevalent disease worldwide and the most prevalent dental problem) is a bacterial-infected inflammatory disease that destroys alveolar bone, leading to the loosening of teeth and tooth loss.[18] It affects individuals throughout their lives, so if it is detected early in the course, the prognosis would be better, thereby improving the overall quality of life.[9] Danks et al. (2021) conducted a study to measure periodontal bone loss due to periodontitis using one of the deep-learning models. He collected a total of 63 periapical radiographs, which included single and multi-rooted teeth and fed the data to a Deep Neural Network (DNN) to detect the dental landmarks, which were then used to calculate the periodontal bone loss. The system showed encouraging results of 89.9%, which can be further enhanced through experimentation and cross-validation with wider data sets.[28]

4.5. Implantology

Dental implants have recently gained popularity and have become the most sought-after treatment for lost teeth. However, post-surgery, there can be mechanical and biological problems in the implant such as implant screw or fixture fractures and inflammation around the implant due to infection. Deep learning can be used to identify any such problems at early stages to improve the life of an implanted tooth.[4] Wonse et al. conducted a study to assess the precision of the deep learning models in identifying and classifying different implant variants. The dataset consisted of 1,56,965 panoramic and periapical radiographs spread over 10 different manufacturers and 27 varieties of dental implant systems. The results showed an accuracy, precision, recall, and F1 score all above 80%.[30]

4.6. Oral and maxillofacial diseases

Cysts and tumors of the jawbone can prove to be one of the most debilitating dental conditions. They are initially painless and asymptomatic, but they quickly grow and impinge on surrounding structures, causing pain, swelling, and pathological fractures.[31] Due to their nature of destruction, early diagnosis and treatment are crucial. Various radiographic modalities, such as CBCT and Magnetic Resonance Imaging (MRI), can be used to identify such lesions. Existing deep learning models like GoogLeNet,[17] Mask R-CNN, and YOLO can detect, classify, and localize odontogenic lesions in radiographic images. A new novel neural network known as Deep Odontogenic Lesion Network (DOLNet) has been proposed by Junegyu et al to accurately diagnose certain conditions such as Ameloblastoma, Odontogenic keratocyst, and Dentigerous Cysts from radiographic images surpassing the diagnostic potential of current approaches by 42.4% and that of professional clinicians by 19.2%.[17]

5. Discussion

The fields of artificial intelligence and deep learning are evolving rapidly to meet the growing demands of both medicine and dentistry. However, the architectural intricacy of these deep learning models makes it difficult for clinicians to apply them in day-to-day practice. Therefore, it has become a necessity for clinicians to learn and understand the workings of artificial intelligence to make use of these models. It is the dental institutions that have to take the onus of introducing AI as a subject in the curriculum and teach future clinicians about its function, benefits, and practical applications.[31,32]

The ability of deep learning models to accurately and autonomously analyze complex radiographs by automating tasks like object detection, classification, and segmentation can assist clinicians in picking up a range of dental pathologies from simple tooth caries to complex lesions. Additionally, they can reduce the time taken and the manpower for these tasks and reduce overall human errors. Studies on different deep learning models have shown that they can be relied on for the accurate identification of pathologies and for devising an appropriate treatment plan. While the technical intricacies and practical difficulties of deep learning may seem daunting for many dental professionals, understanding its potential impact is crucial.[33]

As discussed earlier in this paper, the key to the success of AI models is the use of good quality and quantity of data. However, in the dental and medical fields, due to the absence of standardized patient data storage, maintenance practices, and government policies, patient data is often haphazard and difficult to access. Additionally, the sensitivity of medical datasets poses ethical and legal concerns. The quality of the dental radiographic data diminishes with poor-quality images and non-standardized exposure settings. To overcome this, the researchers have to select, curate, and preprocess these datasets to craft a high-efficacy and bias-free deep learning model. To overcome these challenges, dental AI research must adhere to standardized protocols and use a diverse range of data to avoid bias.

6. Conclusion

Artificial Intelligence and Deep Learning have immense potential to change the current dental practice methods for improvement in the accuracy of diagnosis, treatment planning, and patient care. Despite their current applicability, there is much scope for development and improvement to a level where they can be indispensable tools in everyday dental practice. Abundant research, development, and collaboration must happen between medical professionals and AI developers to bridge the gap between human expertise and advanced computational analysis and to fully utilize the potential of Deep Learning. Soon, Dental clinicians may expect numerous deep-learning algorithms to assist them in precisely practicing dentistry by providing accurate diagnoses and individualized treatment.

7. Conflict of Interest

The authors declare no conflicts of interest.

8. Source of Funding

None.

9. Acknowledgement

None.

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Cite this article: Shanmugam H, Airen L, Rawat S. Deep learning in dental radiographic image analysis: A review. *J Dent Panacea*. 2025;7(2):72-76.