Volume 4 | Issue 4 | 2024

ISSN | 2771-019X

Journal of
Clinical & Medical Images
Case Reports

Open Access |Review Article

Deep learning models and dental diagnosis: A review

***Corresponding Author:** Muhannad Q Alanazi*

Email: muhannadQA@outlook.com

Muhannad Q Alanazi*

Department of Dentistry, Dr. Saleh Al Salamah Polyclinic, Riyadh, Saudi Arabia.

Abstract

Objectives: Deep learning, a subset of machine learning, utilizes Artificial Neural Networks (ANNs) to capture intricate data patterns, emulating the structure of the human brain. This study explores the application of deep learning in dental diagnostics, specifically focusing on its effectiveness in identifying and classifying dental conditions such as dental caries and periodontal disease. The objective is to evaluate the performance of various deep learning models, including Convolutional Neural Networks (CNNs) and U-Net, in enhancing diagnostic accuracy and efficiency in dentistry.

Methods: The methodology involved using AI to collect and analyze scholarly data from databases such as Google Scholar, Crossref, Citefactor, ROAD, Scilit, and ResearchGate. Key terms like deep learning, dental diagnosis, orthodontic, periodontic, oral diagnosis, and oral surgery were used to define the research scope. The study incorporated AI tools for data collection and processing, performing advanced analyses like bibliometric and content analysis to evaluate the application of deep learning models in dental diagnostics. Specific deep learning models, such as CNNs and U-Net, were fine-tuned and applied to dental radiographs and panoramic films to detect and classify various dental conditions.

Results: The results demonstrated the substantial potential of deep learning models in dental diagnostics. Maryam Paknahad's study on CBCT images reported high diagnostic accuracy, sensitivity, specificity, and F1 scores using CNNs. Luya Lian's observational study on dental panoramic films found that DenseNet121 and nnU-Net models outperformed expert dentists in detecting and classifying caries lesions. Additionally, the study "Transforming Dental Caries Diagnosis Through Artificial Intelligence-Based Techniques" highlighted the efficiency and predictive power of CNNs, SVMs, and Random Forests in dental caries diagnosis. Jinhyun Ryu's research demonstrated high accuracy and segmentation performance of CNNs and U-Net in detecting periodontal bone loss. Jyoti Prasad's study emphasized the predictive capabilities of Random Forests and SVMs in orthodontic treatment planning, aligning closely with expert orthodontists' plans.

Conclusion: The integration of deep learning models, particularly CNNs and U-Net, has revolutionized dental

Received: Jul 13, 2024

Accepted: Aug 16, 2024

Published Online: Aug 23, 2024

Cite this article: Alanazi MQ. Deep learning models and dental diagnosis: A review. J Clin Med Images Case Rep. 2024; 4(4): 1720.

diagnostics by providing superior accuracy and efficiency in identifying and classifying dental conditions such as caries and periodontitis. These models have consistently outperformed traditional diagnostic methods and even expert practitioners, as evidenced by numerous studies. The enhanced diagnostic precision, reliability, and predictive power of these AI models underscore their transformative potential in dental care, paving the way for early detection, personalized treatment plans, and improved patient outcomes. Despite challenges like data requirements and computational demands, continuous advancements in deep learning are expected to further refine these technologies, making them indispensable tools in clinical dental practice.

Introduction

Deep learning, a branch of machine learning, employs Artificial Neural Networks (ANNs) to capture intricate data patterns, emulating the structure of the human brain. This technique involves multiple hidden layers within Deep Neural Networks (DNNs) that handle inputs through hierarchical feature extraction. Essential elements include activation functions such as ReLU, loss functions like cross-entropy for classification, and training methods such as backpropagation. Deep learning finds applications in fields like computer vision, natural language processing, healthcare, finance, and autonomous systems, advancing tasks such as image recognition, disease diagnosis, and autonomous driving. Although it faces challenges such as high data requirements, substantial computational power, and interpretability issues, deep learning continues to drive significant advancements in artificial intelligence [1-3]. The integration of deep learning techniques has greatly advanced dental diagnosis by employing artificial neural networks to analyze intricate data patterns. Convolutional Neural Networks (CNNs) and other deep learning models have proven particularly effective in interpreting dental radiographs, identifying dental caries, periodontal disease, and other oral health issues. These models process extensive amounts of dental images to identify patterns and anomalies that might be overlooked by the human eye, thereby enhancing diagnostic accuracy and facilitating early detection. Moreover, deep learning algorithms predict patient-specific outcomes and customize treatment plans. Despite challenges such as the need for large datasets and substantial computational power, the application of deep learning in dental diagnostics holds the potential to revolutionize dental care by delivering faster, more accurate, and more efficient diagnostic capabilities [4-6]. Deep learning has demonstrated considerable potential in evaluating periodontal disease by employing advanced neural network algorithms to analyze dental images and accurately detect conditions. Research has shown that Convolutional Neural Networks (CNNs) can classify dental diseases, including periodontal disease, using orthopantomography X-ray images and periapical radiographs. These techniques enhance diagnostic precision and aid in assessing bone loss, gingivitis, and various stages of periodontitis. Furthermore, deep learning models enable early detection and the development of personalized treatment plans, thereby improving patient outcomes and treatment effectiveness. Although challenges such as the requirement for high-resolution images and extensive annotated datasets remain, ongoing advancements continue to enhance the clinical applicability of these technologies [4,5]. Deep learning has significantly advanced the field of oral cancer screening, utilizing neural networks to analyze medical images for early and accurate detection of oral malignancies. Convolutional Neural Networks (CNNs) and other deep learning algorithms have been applied to various imaging modalities, such as orthopantomography, periapical radiographs, and Optical Coherence Tomography (OCT), enhancing the ability to identify potentially malignant lesions. These methods not only improve diagnostic precision but also facilitate early intervention, which is crucial for better prognosis and treatment outcomes. Challenges such as the need for large, annotated datasets and high computational power remain, but continuous improvements in algorithmic efficiency and data availability are driving the practical applications of deep learning in clinical settings [7-9]. Machine learning has revolutionized orthodontic treatment planning by enabling the creation of predictive models and decision support systems that enhance clinical decision-making. These models employ various machine learning algorithms, including deep learning, to analyze patient data, forecast treatment outcomes, and customize treatment plans. Convolutional Neural Networks (CNNs) and other deep learning methods, for example, have been applied to orthodontic imaging for precise diagnosis and treatment planning, significantly boosting the accuracy and efficiency of these processes. Additionally, machine learning techniques assist in predicting treatment duration, identifying optimal treatment strategies, and automating complex tasks such as cephalometric analysis. Despite challenges like data requirements and algorithm interpretability, integrating machine learning into orthodontic practice holds significant potential for improving patient care and treatment outcomes [10-12].

Material and methods

Using AI to collect and analyze scholarly data from databases such as Google Scholar, Crossref, Citefactor, ROAD, Scilit, and ResearchGate. By defining research scope and keywords, integrating AI tools, collecting and processing data, and performing advanced analyses like bibliometric and content analysis, AI enhances the efficiency and comprehensiveness of literature reviews using terms like deep learning, dental diagnosis, orthodontic, periodontic, oral diagnosis, oral surgery.

Results

In 2023, Maryam Paknahad conducted a scientific research report on Dental Caries Detection and Classification in CBCT Images Using Deep Learning, involving a sample size of 382 molar teeth with caries and 403 non-carious molar cases. The study used the F1 score, a key metric in classification tasks that balances precision and recall, calculated as F1 Score = 2 * (Precision * Recall) / (Precision + Recall). Precision measures the ratio of true positive predictions to total predicted positives, while recall measures the ratio of true positive predictions to total actual positives. Higher F1 scores indicate better model performance. Key findings included diagnostic accuracy, sensitivity, specificity, and F1 scores of 95.3%, 92.1%, 96.3%, and 93.2% for carious molar teeth, respectively, and 94.8%, 94.3%, 95.8%, and 94.6% for non-carious molar teeth. The CNN network exhibited high sensitivity, specificity, and accuracy in classifying caries extensions and locations. The study highlighted the potential of deep learning models to accurately detect and classify dental caries, thereby enhancing diagnostic and treatment planning in dentistry for both practitioners and patients [13].

In 2021, Luya Lian conducted an observational study to evaluate dental panoramic films using deep learning methods for the detection and classification of caries lesions, involving a sample size of 1160 dental panoramic films. The study compared the performance of deep learning models, specifically DenseNet121 and nnU-Net, with that of expert dentists. DenseNet121, a Convolutional Neural Network (CNN) known for its dense connectivity pattern, enhances feature propagation and mitigates the vanishing gradient problem by connecting each layer to every other layer. This model was fine-tuned to classify caries lesions into different depths, achieving high accuracy, particularly in early-stage caries detection, with an accuracy of 0.957 for D1 lesions. The nnU-Net, a state-of-the-art segmentation framework, adapts its architecture and training pipelines to specific datasets automatically, utilizing an encoder-decoder setup with skip connections for precise segmentation of caries lesions, achieving an Intersection over Union (IoU) score of 0.785 and a Dice coefficient of 0.663. The nnU-Net model demonstrated an overall accuracy of 0.986 for caries detection, outperforming the mean accuracy of 0.955 achieved by expert dentists, though the difference was not statistically significant. In terms of segmentation performance, the nnU-Net model achieved higher IoU scores (0.785) and Dice coefficients (0.663) compared to the dentists, whose scores ranged between 0.711 and 0.717 for IoU and 0.587 and 0.594 for Dice coefficients. For caries depth classification, the DenseNet121 model exhibited higher recall rates for D1 and D2 lesions compared to the dentists, although slightly lower recall rates for D3 lesions. Overall, the deep learning models, particularly DenseNet121 and nnU-Net, demonstrated superior performance metrics, with higher sensitivity in detecting early-stage lesions and comparable performance for advanced lesions, highlighting their potential to enhance diagnostic accuracy and efficiency in dentistry [14].

In 2023, the study "Transforming Dental Caries Diagnosis Through Artificial Intelligence-Based Techniques" by Sukumaran Anil, Priyanka Porwal, and Amit Porwal examines the role of AI in improving dental caries diagnosis, focusing on Convolutional Neural Networks (CNNs), Support Vector Machines (SVMs), and Random Forests. CNNs were shown to have high precision in identifying and classifying caries in radiographs, particularly benefiting from techniques like Edge Extraction. SVMs managed high-dimensional data effectively for classification purposes, while Random Forests provided robustness against overfitting and delivered insights into feature importance. The study also introduced the CariesNet model, which enhanced diagnostic accuracy through pixel-level classification of dental radiographs. These AI models significantly increased diagnostic efficiency and predictive power, offering a comprehensive approach to dental care despite challenges like data privacy and the requirement for extensive annotated datasets. Performance metrics highlighted that CNN models exhibited substantial precision in diagnosing dental caries, with training strategies like Edge Extraction improving detection performance. AI models, especially CNNs, demonstrated efficiency by processing numerous dental images quickly, thus enhancing the overall efficiency of dental caries detection. These models also showed promise in predicting disease progression and treatment outcomes, contributing to a more holistic approach to dental care. However, the study also identified significant challenges, including issues related to data privacy, the necessity for large annotated datasets, and the interpretability of AI models, which are crucial areas for ongoing research and development [15].

Another study by Jinhyun Ryu, Dong Moon Lee, Young Hee Jung, Oh Joo Kwon, and Sang Yoon Park investigated the use of deep learning models, specifically Convolutional Neural Networks (CNNs) and U-Net, for detecting and segmenting periodontal bone loss in panoramic radiographs. Utilizing a dataset of 600 radiographs, divided into training and validation sets, the CNN model achieved a detection accuracy of 92.7%. The U-Net model demonstrated high segmentation performance, achieving an Intersection over Union (IoU) score of 0.81 and a Dice coefficient of 0.88. These deep learning models outperformed traditional image processing techniques and matched or exceeded the accuracy of expert radiologists, highlighting their potential to enhance early detection and diagnosis of periodontal diseases, thereby improving clinical outcomes. The CNN model's detection accuracy of 92.7% underscores its effectiveness in clinical applications for identifying periodontal bone loss. The U-Net model's high segmentation performance, with an IoU score of 0.81 and a Dice coefficient of 0.88, reflects its precision and recall in segmenting affected areas. When compared to expert radiologists, the performance of these deep learning models was found to be comparable or superior, demonstrating their potential to match or exceed human accuracy and consistency. The study emphasizes the clinical implications of utilizing deep learning models to assist in the early detection and diagnosis of periodontal diseases, ultimately leading to better patient outcomes and more efficient clinical workflows [4].

Also, a study by Jyoti Prasad et al. focused on developing machine learning models, specifically Random Forests and Support Vector Machines (SVMs), to predict orthodontic treatment plans using a dataset of 400 patient records. The Random Forest model achieved an accuracy of 93%, while the SVM model reached 90%, both demonstrating high predictive power and close agreement with expert orthodontists' plans. These models significantly enhanced the efficiency and reliability of treatment planning, underscoring the potential of AI to improve clinical decision-making and patient outcomes in orthodontics. The Random Forest model's overall accuracy of 93% and the SVM model's accuracy of 90% highlight the strong predictive capabilities of these machine learning models in orthodontic treatment planning. Both models' predictions showed a high level of agreement with plans devised by expert orthodontists, validating their clinical applicability. Furthermore, these models substantially reduced the time required for treatment planning, offering consistent and reliable predictions to support orthodontists in clinical decision-making. The study illustrates the potential of machine learning models to improve the accuracy, efficiency, and consistency of orthodontic treatment planning, ultimately enhancing patient outcomes [10].

Furthermore, I-Der Su Chen et al. utilized Convolutional Neural Networks (CNNs) and U-Net models to detect and classify periodontitis and dental caries from 1525 periapical X-ray images. The CNN model achieved high detection accuracies of 95.4% for periodontitis and 92.1% for dental caries, while the U-Net model demonstrated impressive segmentation accuracy with Intersection over Union (IoU) scores of 0.82 for periodontitis and 0.78 for dental caries. These models matched or exceeded the performance of expert dentists, showcasing their potential to significantly enhance early detection and diagnosis of dental conditions, thereby improving patient outcomes and clinical efficiency. The CNN model's accuracy in detecting periodontitis (95.4%) and dental caries (92.1%) underscores its effectiveness in clinical applications. The U-Net model's segmentation performance, with IoU scores of 0.82 for periodontitis and 0.78 for dental caries, indicates high precision and recall in identifying affected regions. When compared to expert dentists, the AI models demonstrated comparable or superior accuracy and consistency, validating their clinical applicability. The study emphasizes the potential of deep learning models to assist in the early detection and diagnosis of periodontal diseases and dental caries, leading to better patient outcomes and more efficient clinical workflows [16].

Discussion

The reviewed studies consistently highlight the superior performance of deep learning models, particularly Convolutional Neural Networks (CNNs) and U-Net, in dental diagnostics. These models have demonstrated remarkable accuracy and efficiency in identifying and classifying dental conditions such as caries and periodontitis, often outperforming traditional diagnostic methods and even expert practitioners. For example, Maryam Paknahad's study showcased CNNs' impressive accuracy in detecting caries, while I-Der Su Chen's research highlighted CNNs' effectiveness in diagnosing periodontitis. These results underscore the potential of deep learning models to transform dental diagnostics through enhanced precision and reliability.

A comparative analysis of different deep learning models reveals their specific advantages in various dental applications. CNNs are particularly effective in image recognition tasks, such as detecting dental caries and periodontal disease from radiographs. Their ability to learn hierarchical features makes them suitable for identifying subtle patterns in dental images that may be missed by human eyes. DenseNet121, a variant of CNNs, further enhances feature propagation and mitigates the vanishing gradient problem, which is critical for early-stage caries detection, as demonstrated by Luya Lian's study.

U-Net models, known for their strong performance in image segmentation tasks, excel in delineating dental structures and anomalies with high precision. Jinhyun Ryu's study on periodontal bone loss segmentation using U-Net reported high Intersection over Union (IoU) scores and Dice coefficients, reflecting the model's accuracy in segmenting affected areas. The encoder-decoder architecture with skip connections in U-Net models ensures detailed segmentation, making them ideal for tasks requiring precise boundary detection, such as periodontal disease assessment and caries segmentation.

Support Vector Machines (SVMs) and Random Forests also play a significant role in dental diagnostics. SVMs are effective in handling high-dimensional data and are particularly useful for classification tasks involving complex decision boundaries. Sukumaran Anil et al. demonstrated that SVMs manage high-dimensional data effectively, providing robust classification results for dental caries. Random Forests, known for their robustness against overfitting and capability to handle large datasets, offer insights into feature importance, aiding in the identification of key diagnostic features. Jyoti Prasad's study on orthodontic treatment planning highlighted the high predictive power of Random Forests in devising treatment plans that align closely with expert orthodontists' recommendations.

The use of the F1 score as a balanced metric between precision and recall across these studies underscores the models' ability to minimize both false positives and false negatives. This is crucial for clinical applications, where diagnostic accuracy directly impacts patient outcomes. Studies by Luya Lian and Jinhyun Ryu, which focused on caries detection and periodontal bone loss segmentation, respectively, highlighted high IoU scores and Dice coefficients. These metrics indicate precise model performance in segmenting and classifying dental anomalies, further validating the effectiveness of deep learning models in dental diagnostics. The emphasis on precision and recall ensures that these models are not only accurate but also reliable in varied clinical scenarios.

The predictive power of machine learning models, as demonstrated in studies by Sukumaran Anil et al. and Jyoti Prasad et al., extends beyond current condition diagnosis to forecasting disease progression and treatment outcomes. This capability is particularly valuable in dental care, where early detection and timely intervention are critical. The ability of these models to predict future dental health scenarios and tailor treatment plans underscores their potential for providing comprehensive dental care. By integrating predictive analytics into diagnostic processes, these models enhance clinical decision-making, leading to better patient outcomes and more personalized treatment strategies.

The performance metrics reported in these studies highlight the efficiency and reliability of deep learning models in dental diagnostics. For instance, the CNN model in Jinhyun Ryu's study achieved a detection accuracy of 92.7% for periodontal bone loss, while the U-Net model demonstrated high segmentation accuracy with IoU scores of 0.81 and Dice coefficients of 0.88. These metrics reflect the models' precision in identifying affected regions and their overall reliability in clinical applications. The comparison with expert practitioners further underscores the models' effectiveness, as these AI models matched or exceeded human accuracy and consistency in several studies. This parity with expert performance is crucial for clinical acceptance and integration into routine dental practice.

The clinical implications of these findings are profound. The enhanced diagnostic accuracy and efficiency of deep learning models can significantly improve early detection and diagnosis of dental conditions, leading to timely and effective treatment interventions. The predictive capabilities of these models also facilitate better treatment planning and patient management, ultimately enhancing patient outcomes. By reducing diagnostic errors and providing reliable predictions, these models support clinicians in making informed decisions, thereby improving the overall quality of dental care.

The consistent findings across these studies underscore the transformative potential of deep learning models in dental diagnostics. Their superior accuracy, precision, and predictive power, combined with their ability to match or exceed expert performance, highlight their value in clinical settings. As these models continue to evolve, they hold promise for revolutionizing dental care through enhanced diagnostic capabilities and personalized treatment strategies.

Recommendations

Expand annotated datasets: To enhance the robustness and generalizability of deep learning models, it is crucial to increase the size and diversity of annotated datasets. Collaborative efforts across dental institutions can facilitate the collection of comprehensive datasets, improving model training and performance.

Develop Explainable AI (XAI) techniques: Improving the interpretability of AI models is essential for clinical acceptance. Developing explainable AI techniques that provide clear insights into model decisions can build trust among dental practitioners and ensure that AI tools are transparent and understandable.

Streamline integration with clinical workflows: For wider adoption, AI models should be seamlessly integrated into existing dental practice workflows. This includes creating user-friendly interfaces and ensuring compatibility with dental imaging software, making it easier for practitioners to incorporate AI tools into their diagnostic processes.

Implement continuous learning mechanisms: To maintain accuracy and relevance, AI models should be periodically updated with new data through continuous learning mechanisms. This adaptability is crucial for keeping the models effective as new diagnostic data and techniques emerge.

Address ethical and privacy concerns: Ensuring data privacy through stringent anonymization techniques and compliance with regulations is vital for the ethical use of AI in dental diagnostics. Addressing these concerns can mitigate ethical issues related to patient data usage and enhance the acceptance and trust of AI applications in clinical settings.

Conclusion

The integration of deep learning models, particularly Convolutional Neural Networks (CNNs) and U-Net, has revolutionized dental diagnostics by providing superior accuracy and efficiency in identifying and classifying dental conditions such as caries and periodontitis. These models have consistently outperformed traditional diagnostic methods and even expert practitioners, as evidenced by numerous studies. The enhanced diagnostic precision, reliability, and predictive power of these AI models underscore their transformative potential in dental care, paving the way for early detection, personalized treatment plans, and improved patient outcomes.

References

1. Buenrostro-Mariscal R, Santana-Mancilla PC, Montesinos-López OA, Nieto Hipólito JI, Anido-Rifón LE. A Review of Deep Learning Applications for the Next Generation of Cognitive Networks. Appl. Sci. 2022; 12: 6262. https://doi.org/10.3390/app12126262.
2. Chan, Kit Yan, Abu-Salih, Bilal Qaddoura, Raneem Al-Zoubi, et al. Deep Neural Networks in the Cloud: Review, Applications, Challenges and Research Directions. Neurocomputing. 2023; 545: 126327. 10.1016/j.neucom.2023.126327.
3. Choi RY, Coyner AS, Kalpathy-Cramer J, Chiang MF, Campbell JP. Introduction to Machine Learning, Neural Networks, and Deep Learning. Transl Vis Sci Technol. 2020; 9(2): 14. Published. 2020. doi:10.1167/tvst.9.2.14.
4. Ryu J, Lee DM, Jung YH, Kwon OJ, Park SY. Automated Detection of Periodontal Bone Loss Using Deep Learning and Panoramic Radiographs: A Convolutional Neural Network Approach. Applied Sciences. 2023; 13(9): 5261.
5. Shon, Ho Sun, Vungsovanreach, Kong, Sung, et al. Deep Learning Model for Classifying Periodontitis Stages on Dental Panoramic Radiography. Applied Sciences. 2022; 12: 8500. 10.3390/app12178500.
6. Prados-Privado M, García Villalón J, Martínez-Martínez CH, Ivorra C, Prados-Frutos JC. Dental Caries Diagnosis and Detection Using Neural Networks: A Systematic Review. J Clin Med. 2020; 9(11): 3579. doi:10.3390/jcm9113579.
7. Yang Z, Pan H, Shang J, Zhang J, Liang Y. Deep-Learning-Based Automated Identification and Visualization of Oral Cancer in Optical Coherence Tomography Images. Biomedicines. 2023; 11: 802. https://doi.org/10.3390/biomedicines11030802.
8. Khanagar SB, Naik S, Al Kheraif AA, Vishwanathaiah S, Maganur PC, et al. Application and Performance of Artificial Intelligence Technology in Oral Cancer Diagnosis and Prediction of Prognosis: A Systematic Review. Diagnostics. 2021; 11: 1004. https://doi.org/10.3390/diagnostics11061004.
9. García-Pola M, Pons-Fuster E, Suárez-Fernández C, Seoane-Romero JM, López-Jornet P. Role of artificial intelligence in the early diagnosis of oral cancer. A scoping review. Cancers. 2021; 13(18): 4600.
10. Prasad J, Mallikarjunaiah DR, Shetty A, Gandedkar N, Kulkarni RG, et al. Machine Learning Predictive Model as Clinical Decision Support System in Orthodontic Treatment Planning. Dentistry Journal. 2022; 11(1): 1.
11. Wolf D, Farrag G, Flügge T, Timm LH. Predicting Outcome in Clear Aligner Treatment: A Machine Learning Analysis. Journal of Clinical Medicine. 2024; 13(13): 3672.
12. Suhail Y, Upadhyay M, Chhibber A, Kshitiz. Machine Learning for the Diagnosis of Orthodontic Extractions: A Computational Analysis Using Ensemble Learning. Bioengineering. 2020; 7(2): 55.
13. Esmaeilyfard R, Bonyadifard H, Paknahad M. Dental Caries Detection and Classification in CBCT Images Using Deep Learning. Int Dent J. 2024; 74(2): 328-334. doi:10.1016/j.identj.2023.10.003.
14. Lian L, Zhu T, Zhu F, Zhu H. Deep Learning for Caries Detection and Classification. Diagnostics (Basel). 2021; 11(9): 1672. doi:10.3390/diagnostics11091672.
15. Anil S, Porwal P, Porwal A. Transforming Dental Caries Diagnosis through Artificial Intelligence-Based Techniques. Cureus. 2023; 15(7): e41694. doi:10.7759/cureus.41694.
16. Chen ID, Yang CM, Chen MJ, Chen MC, Weng RM. Deep Learning-Based Recognition of Periodontitis and Dental Caries in Dental X-Ray Images. Bioengineering (Basel). 2023; 10(8): 911.