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ARTIFICIAL INTELLIGENCE-ASSISTED EARLY DETECTION OF OCCLUSAL AND PERIODONTAL CHANGES FOR PERSONALIZED PREVENTIVE DENTAL CARE

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ABSTRACT:
Disorders of occlusion and periodontal diseases are among the most prevalent oral health disorders and remain one of the primary reasons for functional impairments, tooth loss, and low quality of life. In order to prevent further development of such disorders and to ensure good oral health status in the future, it is vital to identify pathological changes at an early stage. With the advancements in artificial intelligence (AI), there are new opportunities for enhancing diagnostic precision, monitoring, and individual preventive treatment in dentistry. This review paper is aimed at discussing the biological association between modification of occlusion and periodontal diseases, as well as current state of applying AI technologies in the early diagnosis and management of periodontal diseases. Machine learning, deep learning, computer vision, and predictive analytics in the analysis of radiographic images, intraoral scans, clinical histories, biomarker profiles, and other functional data are emphasized in the current review paper. It is possible to highlight the ability of AI-assisted systems to diagnose teeth wear, monitor orthodontic movement, assess periodontal bone loss, evaluate TMD, and predict the course of the disease. Moreover, multimodal AI approaches, incorporating clinical, imaging, behavioral, and biological information, contribute to the transition to precision dentistry and tailored preventive approaches. Although considerable achievements have been made, there are still some issues affecting the application of the models clinically, namely, low interpretability, validation of the model and quality of the data, privacy concerns, and ethics of governance. Innovations like digital twins, federated learning, and intelligent decision support systems are likely to improve predictive power and personalized approach of providers. In summary, AI can bring about a revolution in preventive dental care, allowing for intervention at an early stage and management of risks.

KEYWORDS: Artificial intelligence, Periodontal disease, Occlusal changes, Precision dentistry, Preventive dental care.

1. INTRODUCTION

Oral diseases are considered one of the most common chronic diseases in the world and continue to be a significant individual, health-care and economic burden. Oral disorders, such as periodontal diseases and tooth loss, untreated dental conditions are estimated to affect billions of people worldwide and are expected to grow in numbers dramatically over the next few decades as a result of population growth, population ageing and the unequal access to oral health care [1]. Of these conditions, periodontal disease and occlusal abnormalities are significant due to their progressive nature and the potential of negatively affecting oral function, esthetics and quality of life. As a result new approaches are needed which can detect pathological changes early and can therefore offer timely interventions for preventing these changes.

Periodontal diseases are chronic inflammatory conditions accompanied by the destruction of the supporting structures of the teeth – gingiva, periodontal ligament and alveolar bone. Without treatment, they can cause the teeth to become loose and fall out. Tooth loss and edentulism continues to be a significant public health problem, especially among adults. Epidemiological studies have shown significant long-term trends in disability due to edentulism, and preventive measures that can maintain natural teeth for life are important [2]. Age-related physiological changes, systemic comorbidities and difficulties in maintaining oral hygiene render older adults as a vulnerable group for periodontal breakdown. There is thus a greater emphasis on prevention and early management in the modern treatment of periodontology [3].

In addition to periodontal disease, occlusal changes, such as occlusal wear, excessive occlusal forces, tooth migration and abnormal tooth contacts can impact oral disease outcome. Although occlusion doesn't seem to be a primary etiological component in periodontal disease, there is increasing evidence that occlusal forces may exacerbate the ongoing periodontal destruction, because of the excessive mechanical forces to already compromised periodontal supporting tissues [4]. Furthermore, occlusion and the dynamics of periodontal tissues play a more significant role in the tissues' adaptation process and the stability of orthodontics in the remodeling process [5]. Thus it is essential to observe these alterations early in the course of the disease to minimize or prevent any irreparable alterations and maximize treatment.

Diagnostic procedures for occlusal/periodontal abnormalities are more traditional in nature and include clinical examination, radiograph, periodontal probing and the clinical experience of the clinician. While all these are important ways, they are subjective, can vary between different examiners and may not be able to detect subtle changes in the biology before clinical signs begin. The shift from treatment to prevention and personalisation in oral health care is increasing and a technology is needed to continuously monitor oral health, integrate multiple data streams from the patient and predict disease before a clinically significant loss of tissue.

The new possibilities, that have been driven by the recent developments in Artificial Intelligence (AI), allow tackling these challenges in an unprecedented way. AI encompasses a collection of algorithms and computational techniques, including machine learning, deep learning, computer vision and predictive analytics, which enable computers to detect patterns and make clinically relevant insights from vast and intricate datasets. There have been many areas where artificial intelligence technology has shown its potential in dentistry such as in image interpretation, classification of diseases, treatment planning and even predicting risks. Such technologies have increasingly become popular for use in the process of clinical decision-making and even in EBPM [6].

In addition to this, advanced and cutting-edge technologies developed in the area of digital dentistry, wearable, flexible electronics and smart sensing are transforming the landscape of oral disease prevention. Advanced diagnostic tools for oral cavity can be used to acquire information in real time from occlusal forces, periodontal condition, saliva biomarkers, patient behavior, etc., which can be analyzed using AI technology. As a consequence of these advances, there is a new generation of preventive diagnostics where continuous surveillance, early detection of disease and personalisation of approach towards intervention are very important.

In this context, AI technologies for early detection of occlusal and periodontal changes can be a step towards precision dentistry. Information from clinical, radiographic, biomechanical, and biological studies can be used to identify patients who are more prone to IDP, allowing for the prediction of disease progression and therefore, implementation of appropriate preventive measures using AI [7]. Thus, the purpose of this paper is to give a brief overview of the current literature on AI-assisted occlusal and periodontal changes and its future perspectives in developing intelligent dental healthcare systems.

2. Biological and Clinical Basis of Occlusal and Periodontal Changes

Balance between occlusion, periodontal tissue condition, host immunology, and oral microflora is critical to maintaining oral health. Imbalance in any of these parameters can cause biologic reactions, which if continued for long periods of time and with considerable strength, can result in pathological changes in tooth attachment apparatus and masticatory performance. Therefore, the biological and clinical aspects of occlusal and periodontal changes need to be considered in order to develop appropriate strategies for their prevention and diagnosis.

Occlusion is a dynamic process; it consists of interrelated activity of teeth, periodontal ligaments, alveolar bone, masticatory muscles, and temporomandibular joints. During life, physiological adaptations happen throughout life in response to the functional demands, wear of teeth and restorative interventions. Too much occlusal loading, abnormal occlusal contact relationships, parafunctional occlusal habits or tooth migration, however, may upset this balance, and occlusal overload may occur. These changes may be clinically observed as attrition, mobility, fremitus, increased periodontal ligament spaces and decreased masticatory efficiency [8,9]. However, the evidence available now indicates that occlusal forces should not be considered merely mechanical events but biological stimuli that can affect the response of the periodontal tissues and change the structure of the tissues.

Periodontitis is a multifactorial chronic inflammatory disease that is a consequence of a dysbiotic microbial biofilm and progressive loss of periodontal supporting tissues. New theories focus on the idea that pathogens alone are not responsible for the development of disease; rather, disease outbreaks occur when there is an imbalance of the native microbial community and the host's immune system. This shift from microbial symbiosis to dysbiosis is responsible for a chronic inflammatory reaction leading to connective tissue destruction, alveolar bone loss and loss of attachment [10]. There is a vicious cycle between microbial dysbiosis and host inflammation, with inflammation changing the local environment and further promoting the growth of pathogenic microorganisms [11].

For decades, there had been a debate concerning the relationship between occlusal loading and progression of periodontal disease. There is currently no evidence that occlusal overload alone could play a role in starting the process of periodontitis in healthy tissues. However, too much mechanical forces can affect the severity and progression of any existing periodontal lesions, augment tissue stress, modulate cellular signaling pathways and increase inflammatory responses in any stressed periodontal structures [12]. There are experimental and clinical evidence of an increased attachment loss, tooth mobility and alveolar bone changes of overloaded teeth if periodontal inflammation is already present. These findings confirm the notion that biomechanical and inflammatory mechanisms are not mutually exclusive, but are working in concert in periodontal breakdown.

The clinical evaluation of periodontal and occlusal status has been based on probing pocket depth, clinical attachment level, bleeding on probing, tooth mobility, radiographic bone loss, occlusal contacts and functional analyses. Although the indicators listed below are essential for diagnosis, several are indicators of ongoing disease and are not early indicators of disease activity. As a result, it is of great interest to search for biological markers to identify periodontal changes early in the process before irreversible changes occur.

Salivary biomarkers have been receiving much attention among emerging diagnostic tools as they can be collected without surgery and are a reflection of processes happening in the body. Molecules involved in inflammation, tissue degradation, immune responses and bone metabolism have proven to be useful in the detection of individuals at risk for periodontal disease and in monitoring the activity of the disease over time. A number of biomarkers, such as matrix metalloproteinases, inflammatory cytokines and host derived proteins have been found to have good predictive properties for early diagnosis and personalized risk assessment [13].
In sum, existing findings suggest that there are complex interactions between occlusal forces, microbial dysbiosis, host inflammatory reactions and periodontal tissue remodeling. These are not separate factors, but all are part of a dynamic network of biological factors, where mechanical and microbial stresses affect disease susceptibility and progression. A thorough knowledge of these mechanisms gives a scientific basis for new diagnostic methods and will aid the implementation of new technologies for the early diagnosis and prevention of occlusal and periodontal diseases. The main biological and clinical markers linked to occlusal overload and progression of periodontal disease are listed in Table 1 and are indicative of the multifaceted interactions between biomechanical forces, inflammation, dysbiosis of the microbial community, and the activity of biomarkers.

Table 1. Biological and Clinical Indicators of Occlusal and Periodontal Changes

Domain	Key changes	Clinical indicators	Diagnostic relevance	Main sources
Occlusal overload	Excessive or abnormal occlusal forces	Attrition, fremitus, mobility, widened PDL space	Helps identify mechanical stress affecting periodontal stability	[12]
Periodontal inflammation	Host-mediated tissue destruction	Bleeding on probing, pocket depth, attachment loss	Indicates active inflammatory periodontal breakdown	[10]
Microbial dysbiosis	Shift from symbiotic to pathogenic biofilm	Plaque accumulation, persistent inflammation	Explains disease initiation and progression	[11]
Biomarker activity	Molecular signs of tissue degradation	Salivary MMPs, cytokines, host proteins	Supports early and non-invasive risk detection	[13]
Functional disturbance	Altered mandibular or masticatory function	TMJ symptoms, muscle imbalance, abnormal opening	Links occlusion with patient-specific functional risk	[25]

3. Artificial Intelligence Technologies in Dental Diagnostics

With the swift growth of artificial intelligence (AI) has come a revolution in methods of diagnosis, even in the field of dentistry. Artificial intelligence is one of the types of computing systems capable of performing duties that require intelligence of humans. AI applications are gaining popularity in the field of dentistry for simplifying and analyzing complex clinical information, assisting in making an accurate diagnosis and helping in formulating a personalized treatment plan. Applications of big data obtained from radiographs, intraoral scans, clinical documentation, and laboratory investigations by means of AI have been successful in early detection of oral diseases [14].
A primary branch of AI is known as machine learning (ML), which allows for the learning of relationships in data and making predictions without being explicitly programmed to do so. Recently, deep learning (DL) with multilayered artificial neural networks has shown outstanding performance for dealing with large and complex data. Implementing deep learning architectures, especially CNNs, has been great adopted in dentistry due to their capability to automatically learn the relevant features from medical images and reach high diagnostic accuracy. These technologies have increased the use of AI from just classification to complex diagnostic and prognostic systems that can support the clinician along the entire patient care journey [15].
Computer vision is one of the most important fields where AI will be used in dentistry. Computer vision algorithms can be used to automate the interpretation of dental images like periapical radiographs, panoramic radiographs, cone-beam computed tomography (CBCT) scans, and intraoral photographs. AI systems can increasingly accurately segment the image and detect the anatomical structures, pathological change, and measure the severity of the disease using image segmentation and object detection. There is a growing body of evidence that AI-based image analysis can assist with the detection of dental caries, periodontal bone loss, impacted teeth, periapical lesions and other abnormalities in the mouth often with results similar to those of experienced clinicians [16].
The segmentation of images is an important step in computer-aided diagnosis as it allows the precise detection of areas of teeth, alveolar bone and background. Automated segmentation saves the time of manual annotation and enables quantification of oral conditions. Automated systems can be developed for large-scale screening and diagnosis by using deep learning techniques for tooth detection and naming of dental abnormalities in panoramic x-rays [17]. These are especially important in the early detection of occlusal and periodontal changes, subtle changes in the radiograph which may not be noticed at regular check-ups.
In addition to imaging, AI is now also getting used in clinical data management and predictive analytics. Machine learning models can be used to estimate the susceptibility to a disease, predict the outcomes of treatment and help the clinicians identify high-risk individuals by analyzing the electronic health records, demographic data, behavioral risk factors and laboratory findings. This type of predictive systems closely corresponds to precision dentistry, which is based on predicting and adjusting risks to an individual patient. Such techniques have also proven to be clinically relevant in other

medical fields, where the algorithms of machine learning have succeeded to predict outcomes and to stratify the risk among different patient cohorts [18,19].

There is a lot of excitement on the use of AI, but this is going to be difficult to get from predictive models to standard clinical practice and will require careful evaluation. The performance of the test is generally assessed by accuracy, sensitivity, specificity, precision and area under receiver operating characteristic curve (AUC-ROC). But high scores of performance do not imply clinical usefulness. When assessing the reliability of AI solutions, though, external validation, transparency, practical application of the algorithms and quality and generalizability of the data become key aspects that should be considered. Apart from the algorithm's performance, recent publications in medical AI research indicate that one needs to validate the algorithm in relation to different groups and environments for successful implementation [20].

AI methods, including machine learning, deep learning, computer vision and predictive analytics, have transformed it into an important element in dental diagnostics. They could be applied to increase the diagnostic precision as well as help detect oral disorders at early stages and be integrated into automatic image interpretation, risk prediction and clinical decision support systems. Despite there is much more to know about the application of AI in dentistry, with further research, a future will come when these reliable AI tools will become a part of daily work of dentists and contribute to improvement of oral health care. The whole workflow of AI-aided dental diagnostics can be summarized as follows: Multimodal data acquisition, clinically interpretable decision support (as seen in Fig. 1).

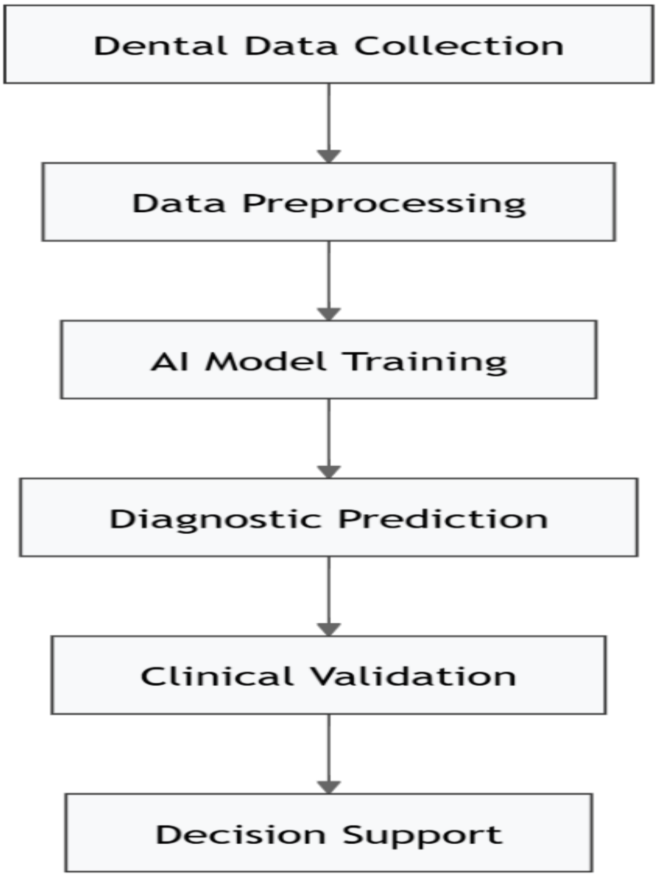

Figure 1. AI Diagnostic Workflow in Dental Diagnostics

4. AI-Assisted Detection of Occlusal Changes

The shift to a digital dentistry has improved the precision in identifying, monitoring and predicting occlusal changes more than the traditional clinical methods. Over time, additional occlusal changes can take place including occlusal discrepancies, functional disturbances, tooth position changes and tooth wear which may not be noticed until there is substantial occlusal damage. The combination of artificial intelligence (AI) and state-of-the-art digital diagnostic tools has opened up new prospects for early detection of these changes, which can be used for preventive and personalized oral care. In today's 21st century, occlusal assessment using technology has become available, including intraoral scanners, digital articulators, computer-based occlusal analysis systems, and three-dimensional imaging platforms. These instruments generate a highly accurate model of dental structures and occlusive relationships, which allows clinical to gain information regarding functional contacts, distribution of forces and changes of morphology over time. However, the application of AI to algorithmic analyses of large datasets and even greater standardisation of diagnostics, enhances such digital processes. The significance of these developments as determinants of precision oral rehabilitation and digitally-assisted treatment planning is increasingly understood [21].

In the context of AI in occlusal assessments, its most prospective usage is connected to automated wear monitoring and diagnosis. Wear is a multidimensional phenomenon, which is related to mechanical, chemical, and behavioral aspects and is complicated to measure clinically. Due to recent improvements in AI-assisted image analysis techniques, it became possible to conduct comparative analysis of sequential intraoral scans and obtain an accurate measurement of even the smallest volume or surface changes. Automated monitoring allows the identification of the first signs of wear and provides an accurate measurement of the wear, which leads to adoption of preventive measures in order to avoid severe wear of tooth structures [22]. AI technologies are increasingly used in evaluation of tooth movements and orthodontic treatment. Through analyzing sequential digital models, photos, and radiographic images, AI systems can detect the changes and make necessary modifications of the treatment protocol. They allow making personal clinical decisions and conduct continuous monitoring of the treatment process and progress in order to facilitate dynamic management of the treatment process. This aspect is especially important in dentistry from the perspective of prevention since early detection of undesirable tooth movements allows decreasing the risk of further occlusion problems [23].

Moreover, the emergence of the remote monitoring platforms has led to the use of AI in orthodontics. With the digital monitoring systems, the patients can submit their pictures and information obtained from their scans at home and then the AI algorithm analyzes the collected information and determines whether there is any problem that should attract the attention of the clinicians. These devices have been extensively tested and found to increase the patient engagement, supervision of the patients' treatment process and early identification of problems when there are discrepancies between the expected outcomes of the treatment and the actual results [24]. Hence, AI-driven remote monitoring plays a crucial role in achieving continuous and personalized occlusal management. Moreover, in addition to structural analysis of the occlusion, AI can be applied in the evaluation of functional occlusal disorders, which involve disorders of the TMJ and masticatory system. TMDs are considered to be multifactorial diseases, meaning that they include numerous factors such as biomechanical, neuromuscular and psychosocial. The different clinical and imaging data may be utilized in making the diagnosis of these diseases. Machine learning and deep learning models were developed to detect TMJ abnormalities, identify the TMD subtype and predict treatment outcome. Recent systematic reviews have shown that AI can improve diagnostic precision and help in clinical decision-making for the management of TMDs [25,26].

Functional analyses of mandibular movements and masticatory muscle activities have also been made possible through techniques using AI. Biomechanical data collected using non-invasive methods can be analysed and used with advanced computational models to assist in predicting patterns of muscle activation, deviations in mouth opening and functional impairments to assist in TMJ dysfunction diagnosis. These skills can be beneficial for clinicians to have a quantitative understanding of occlusal function, and they can supplement the understanding of each patient's unique occlusal biomechanics [27]. As a whole, AI-powered tools are revolutionizing the way occlusal health is evaluated, providing a continuous monitoring, automated analysis, and predictive evaluation of structural and functional occlusal changes. Digital imaging, orthodontic monitoring, functional analysis, and predictive modelling can all help to move away from reactive to proactive, personalised occlusal care, using AI. This agrees with overall precision medicine approach, in which precision risk assessment and early intervention are important components, also for an individual's long-term oral health [28].

5. AI-Assisted Detection of Periodontal Changes

The rapid evolution of artificial intelligence (AI) has transformed the way periodontal diagnosis can be performed because it allows for the identification of changes that could prove difficult to identify by using conventional methods and that would be related to the development of periodontal disease. The periodontal diseases are complex, consisting of a combination of microbial, inflammatory, genetic and environmental factors and diagnosis and monitoring of the disease is challenging. AI has opened up new avenues in periodontal care for enhancing diagnostics, staging, risk prediction, and long-term management of patients [29].

Analysis of these images is one of the areas of periodontology that has been well researched as related to AI. Traditional assessment of periodontal bone loss is the subjective interpretation of the radiographic image which may be subjective and influenced by the quality of the radiograph and the experience of the reader. Automatic detection of anatomical landmarks and measurement of alveolar bone levels, as well as classification of the severity of periodontal destruction can be performed with high consistency using deep learning algorithms. New architectures of neural network have been developed to achieve automated staging of periodontal bone loss, which can help to standardise periodontal bone loss assessment and minimise the inter-clinician variation [30]. Such systems can perform an efficient analysis of a vast number of x-ray images, and can be applied to clinical practice and population-level screening.

AI is not only an interpreter, but it's also contributing to the complete digitalisation of periodontal care. Recent innovations bring together clinical parameters, periodontal probing information, imaging data and patient information on a single digital platform. These systems ensure the ability to evaluate the periodontal status in detail, and to monitor the periodontal disease activity effectively. In recent years, digital periodontal health frameworks have emerged, adopting the idea of data-driven diagnostics, where many different sources of information are combined and analysed together to inform better clinical decision making, and improve preventive care strategies [31].

Another crucial advancement is the integration of biological and molecular information in AI-based diagnostic models. The advent of genomics, proteomics, metabolomics, and microbiome has created massive and complex data sets that can be useful for understanding the susceptibility and progression of disease. AI techniques are excellent to capture meaningful patterns from this multidimensional data and have already demonstrated significant success in other medical domains. Combining the omics information with clinical and radiographic data has a great potential in personalized periodontal risk assessment and precision-based disease management [32].

AI is also promising in monitoring the progression of diseases and predicting recurrence after periodontal treatment. The key to effective long-term management is the ability to recognise those patients at higher risk of future deterioration and thus needing more intensive monitoring. The same prediction strategies have been successfully applied in the field of oncology, where surveillance strategies are defined according to the recurrence pattern and continuous monitoring for

biomarkers [33,34]. These concepts are of growing relevance in periodontology, as disease activity can vary over time and recurrence is even possible after successful initial treatment.
AI can also help monitor periodontal conditions, and with the increasing availability of longitudinal patient data, there are even more opportunities. Repeated clinical, radiographic, and biological measurements can be used to detect subtle trends associated with disease progression with machine learning algorithms. These kinds of longitudinal analytical techniques can help with earlier detection of adverse changes and aid with timely prevention and intervention, to prevent larger tissue damage [35]. The same concept is behind novel approaches for long-term disease management in precision medicine, where instead of disease assessment at discrete points, continuous monitoring is used as the basis for disease management [36].
To sum up, AI-assisted periodontal diagnostics do not only focus on the detection of periodontal disease but also in the staging, prognosis assessment, or recurrence monitoring as well as the individual risk prediction. These technologies integrate radiographic, clinical and biological information and allow a more proactive and individualized approach to the treatment of each patient that may lead to opportunities for earlier intervention and improved long-term oral health outcomes. Table 2 lists the state-of-the-art AI-driven approaches to the detection of occlusal and periodontal modifications, and it is evident that the machine learning and deep learning technologies play a pivotal role in the diagnosis, monitoring, and risk prediction.

Table 2. AI Applications for Early Detection of Occlusal and Periodontal Changes

Application Area	Data Source	AI Technique	Clinical Purpose	References
Tooth wear monitoring	Serial intraoral scans	Image analysis and surface mapping	Detects early wear progression	[22]
Orthodontic monitoring	Digital models and photographs	Machine learning algorithms	Tracks tooth movement and treatment progress	[23,24]
Periodontal bone loss assessment	Panoramic and periapical radiographs	Deep learning segmentation	Automated disease staging	[30]
TMJ and occlusal function analysis	Functional and imaging data	Predictive machine learning models	Supports TMD diagnosis and prognosis	[25,26]
Personalized periodontal risk prediction	Clinical, imaging, and biomarker datasets	Multimodal AI models	Predicts disease progression and recurrence	[29]

6. Multimodal AI and Personalized Preventive Dental Care

Precision Dentistry has changed oral health care from being reactive to a care system based on individual risk assessment, early intervention and prevention. Precision dentistry aims at incorporating all aspects including biological, clinical, behavioral and environmental data to make appropriate decisions for the patient instead of using a standard approach for everyone. As it relates to periodontology and occlusal management, this is especially important as there are significant differences among individuals regarding the susceptibility to disease, progression of disease and response to treatment. With recent developments in artificial intelligence (AI), this transition has been accelerated as it is now possible to analyse complex datasets and make patient-specific preventive recommendations [37].
Multiple sources of patient information is an important part of delivering personalised care. With all of these things in mind, today's dental practice generates all kinds of data, from clinical examination data to radiograph data, intraoral scan data, periodontal measurements, occlusal records, salivary biomarkers and electronic health records. The different types of data can be incorporated into AI algorithms and used to identify patterns which would have been difficult to uncover using conventional assessment techniques. The multi-modal approach not only improves diagnostic precision but also makes it possible to create a complete risk profile of patients [38].
This is exemplified by the integration of periodontology and digital orthodontics, and once again, this highlights the importance of being able to assess risks through data analysis. Occlusal factors, tooth movement patterns, periodontal status, and biological parameters, all of which are included, are now all accessible via digital platforms. Such systems can assist in recognizing individuals at risk of having their periodontal integrity compromised, as well as their occlusal stability or problems linked to their treatment. The use of predictive models with the help of artificial intelligence can be used to accurately predict outcomes and prevent oral health issues from happening in the future [39].
Digital twins for health care have got much attention and are among the novel concepts that have gained much interest. Digital twins are a digital reflection of the real-life individual which is always being updated by real-world data and is capable of simulating biological processes, predicting future events, and evaluating interventions. Digital twins may incorporate the results of radiography, gums measurements, teeth occlusion, biomarker profile, and behavior data to make a personalized model of oral health care in dentistry. They may be able to predict the progression of the disease, its outcome, and even prevent the disease before any serious clinical impact. It has recently been suggested that the importance of digital twins may lie in precision health in other fields [40].
Healthcare systems must also be efficient enough to deliver personalized preventive care. These systems will give AI-derived recommendations on the best approaches for diagnoses, prevention and therapy of particular diseases. With the help of CDSS platforms, it is possible to incorporate the patient data and translate them into valuable information that may optimize clinical workflows, decrease the risks of errors in decision making and reduce their inconsistency. CDSS platforms can be helpful in preventative dentistry by identifying patients who require individualized recall and risk-based periodontal maintenance programs and those who require certain intervention to prevent the development of the disease.

PoCDSS has been proven to influence the quality and efficiency of decision making in the healthcare sector, and this technology can be applied to dentistry as well [41].
Multimodal AI technologies have begun paving the way toward an era of personalized preventive dentistry. With AI, combining various data sets, predictive analytics, digital twin techniques, and decision support systems, the early identification of risks and the development of patient-specific interventions can be possible [42]. The shift in paradigm is taking us a step closer to a true paradigm of precision medicine that is continuous, data-driven, and not based on the occurrence of any clinical disease. Figure 2 illustrates the proposed multimodal AI system for personalized preventive dental care.

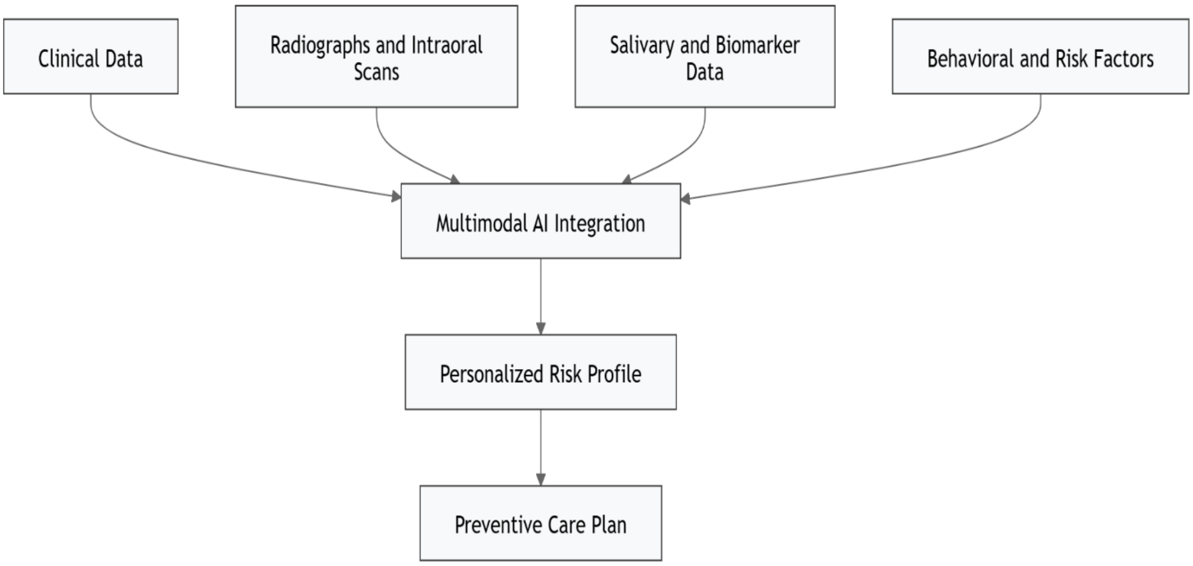

Figure 2. Multimodal AI Framework for Personalized Preventive Dental Care

7. Current Clinical Applications and Evidence Synthesis

Artificial Intelligence (AI) is now moving from the experimental research lab to the everyday clinical practice of dentistry, and is being used to help with diagnosis, treatment planning, patient monitoring and prevention. Integration of AI into clinical workflows is rapidly growing as more and more digital imaging systems, electronic health records and cloud-based analytical platforms become available. In the modern day, some of the uses of radiographs are automated interpretation of the images, caries detection, periodontal evaluation, monitoring orthodontic treatment, prosthodontic treatment planning and prediction of disease progression. These and other innovations are reshaping oral health care, enabling clinicians to more accurately and efficiently diagnose and treat oral health, and all based on data.
A major focus is determining the accuracy of AI systems in comparison to expert healthcare providers. It has been successfully adopted in different areas in medicine, where it proved its ability to work equally to or better than humans in diagnostic purposes based on a sufficient amount of input data. Artificial intelligence models were carefully checked in pattern recognition procedures and showed high sensitivity and specificity and low inter-observer variability. However, it is necessary to highlight that the most researches claimed that artificial intelligence should be regarded as an aid for making decisions but never as a replacement of clinical decision making process, which remains very important in health care field [43]. Artificial intelligence has generally shown excellent results in the integration into clinician-driven workflow, which can also be mentioned about medicine industry.
Telemedicine and telecare have also been made possible by artificial intelligence technology. Through the use of digital communication, the patient is able to send clinical images, intra-oral scans and treatment records from home. This information can then be used by artificial intelligence technology to notify the healthcare professional if there is no effect or abnormality in treatment. They have been successfully applied in orthodontic treatment, preventive care, and periodontal maintenance programs, as they can be useful to encourage patients to maintain their treatment plan and implement timely intervention if any problems are detected. In this way, telemedicine platforms can be great additions to the dental care offered in the traditional clinical context, aided by AI [44].
AI Technologies need to be evaluated in terms of long-term outcomes and an economic impact in addition to diagnostic efficacy. These can translate to improved clinical outcomes and a lower cost of health care, which can be achieved through early disease detection, reduced diagnostic error, improved treatment planning and better prevention. But, the adoption of AI systems may involve significant investments in software, infrastructure, data management, and skilled workforce training. Hence cost-effectiveness analysis is required to evaluate the cost-benefit of the clinical benefits. Economic evaluation frameworks are organized ways of assessing whether a health care technology has a net cost savings benefit relative to the improvement in patient outcomes, quality of care and resource use that it provides [45].
Moreover, there are some limitations associated with the existing body of evidence on the topic. Some of the studies may be retrospective or include small sample sizes. Others may be conducted under highly controlled conditions, which may differ from those used in clinical settings. Furthermore, various studies may differ by their definitions of performance, validation strategies, and AI algorithms used. All these limitations highlight the need to conduct larger prospective studies and to use a common reporting framework and systematic reviews of AI applications in dentistry [46].

The findings overall suggested that the potential of AI is great to improve dental diagnosis, remote patient care, and patient preventative management. Some clinical applications to date indicate that AI may be a helpful aid to enhance and complement professionals' skills to offer more efficient, accurate and individualized oral health care delivery, but more validation is required. Figure 3 provides an overview of how AI is progressing from a solution to support diagnosis, to remote monitoring and assessment, and how it is integrating into the clinic to support patient care.

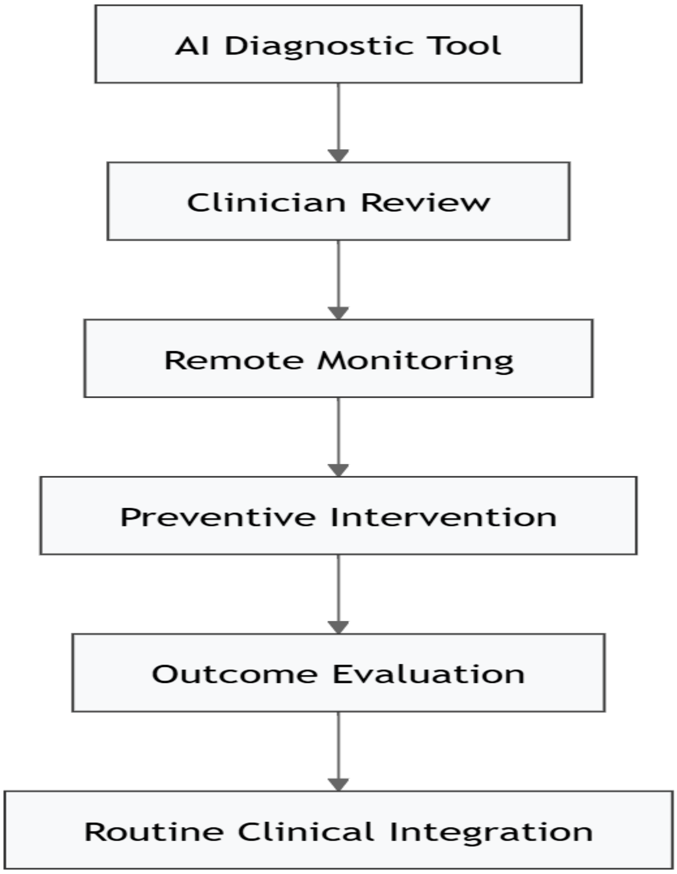

Figure 3. Clinical Translation Pathway of AI in Preventive Dentistry

8. Challenges, Ethical Considerations, and Future Directions

Artificial intelligence (AI) is rapidly evolving in the field of dentistry, yet there are still a number of drawbacks to its use in clinical practice. One of the most important issues is to prevent the development of reliable and generalizable predictive models. The accuracy of many AI systems are trained with small and/or very specific datasets and run the risk of overfitting the model, meaning that the AI model is very precise with the provided dataset and less precise when applied to a new set of patients. Thus, the need for the proper validation methods such as external validation and multicenter validation to reinforce and implement AI-assisted diagnostic devices in clinical practice is very important [47].

Other challenges for implementation are the availability and quality of the data. Healthcare data is fragmented, locked up in silos, and often exists in different institutions and locations, making it difficult to collect and collate such large and varied datasets to create effective AI models. Federated learning is a potential solution to this problem as it enables institutions to collaborate to train a model without sharing sensitive patient information. While these technically and infrastructurally demanding experiences clearly prove the ability of federated solutions to create models and not lose any data ownership or security, it is relevant for the healthcare field [48].

Ethical and privacy concerns must also be addressed. The more artificial intelligence-based solutions are applied, the more patient data is collected and processed, for instance, clinical data, imaging data, or biological measurements. Ensuring the proper use of new technology and preserving patient privacy at the same time is quite a delicate matter. Proper data governance, informed consent, transparency of algorithms, and gaining patient trust are some of the aspects that have to be considered for ethical application of AI. Concerning patients' views, there is consensus about the need to protect patients' privacy and implement comprehensive regulations [49].

This technological innovation in tele dentistry with the use of artificial intelligence technology has brought about some advantages, but challenges to the maintenance of oral health in prevention have also been brought about. Tele-monitoring through mobile devices helps in increasing access to care, monitoring of the condition in real-time and reduces the amount of effort required in the management of the condition. This can only be possible if the digital infrastructure is in place, the clinicians are well trained and regulations exist [50].

Overall, multimodal AI can become an important constituent part of the future of personalized dentistry. Multimodal AI can process such kinds of patient information as imaging data, clinical history, biomarkers profile, behavioral information, and other individual factors. In addition, this approach can help create more personalized prevention and treatment plans due to the high accuracy of their prediction abilities. Therefore, AI-assisted preventive dentistry is very promising for the future, although it has to face some challenges.

Table 3. Opportunities, Challenges, and Future Directions of AI in Personalized Preventive Dentistry

Area	Current Opportunity	Major Challenge	Future Direction	References
Precision dentistry	Individualized risk assessment	Data heterogeneity	Patient-specific preventive models	[37]
Remote monitoring	Continuous patient surveillance	Technology accessibility	AI-integrated teledentistry platforms	[44,50]
Predictive modeling	Early disease prediction	Overfitting and poor generalizability	External and multicenter validation	[47]
Data governance	Secure clinical data utilization	Privacy and ethical concerns	Federated and privacy-preserving learning	[48,49]
Advanced AI ecosystems	Multimodal analytics and digital twins	Integration of diverse datasets	Real-time precision oral healthcare systems	[40]

9. CONCLUSION

The use of AI technology in preventive dentistry will change everything. AI is capable of identifying occlusal and periodontal changes more accurately and at an early stage than any traditional approach. Through its ability to intake and benefit from machine learning, deep learning, computer vision, and predictive analytics, AI is able to assess and help detect diseases, predict risks, and personalize treatment plans based on complex clinical, radiographic, functional, and biological data. There have been attempts at using AI technology for tooth wear monitoring, orthodontic monitoring, staging periodontal disease, TMD assessment and longitudinal monitoring. Using multimodal AI models that integrate information from various sources relevant to a particular patient is also another way through which personalized preventative approaches and clinical decisions can be improved; therefore, reinforcing the concept of precision dentistry. Nevertheless, there are problems associated with data quality, generalizability of models, validation, privacy protection, and ethics that must be addressed before these models can be used clinically. The future is expected to involve advances in continuous oral health monitoring and intervention, including digital twins, decision-support intelligent systems, and AI-based remote monitoring. With continuous validation of AI technology through research and practice, it is poised to become an important aspect of patient-centric dental care, which will change the paradigm from reactivity to proactivity, prediction, and precision in oral health.

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