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# Artificial Intelligence in Dentistry: The Ultimate Panacea for Modern Challenges?

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**Abstract**

Within computer science, artificial intelligence (AI) is the study of developing computers that can carry out activities that normally require human intelligence. AI aims to learn and solve issues similarly to humans. Artificial intelligence has grown and developed dramatically over the past 20 years, primarily due to advances in digital data collection, machine learning, and computing infrastructure. These developments are quickly broadening the applications of AI, even in fields historically dominated by experts. AI is swiftly taking center stage in clinical dentistry procedures. It has enormous potential in dentistry, where it can improve patient care and lead to significant advancements in medical science. Dental AI research is investigating a range of uses, such as pathological and anatomical structure identification, disease diagnosis, treatment outcome prediction, and material selection. AI offers several advantages in the medical field, including a decrease in postoperative complications, an improvement in quality of life, a reduction in needless treatments, and an enhancement in dental surgeons' diagnostic precision. This narrative review investigates the various applications, benefits, challenges, and potential uses of artificial intelligence in dentistry.

**Keywords:** artificial intelligence; dental AI applications; dentistry; diagnostic imaging; ethical considerations; machine learning; robotic dentistry; treatment planning

## Introduction

Artificial intelligence (AI) is the ability of a device to carry out tasks traditionally associated with human intelligence, such as learning, reasoning, and self-improvement. AI is becoming increasingly prevalent in our daily lives [1]. In 1950, Alan Turing raised the question, "Can machines think?" John McCarthy later coined the phrase “Artificial Intelligence”.

Researchers from a variety of professions have long been fascinated by the complex neural networks found in the human brain [2,3]. Fully recreating the human brain is still unattainable, despite scientific progress leading to the development of sophisticated technology that replicates brain activities [4]. AI's relentless advancement has made it more and more important in all spheres of life, despite many obstacles [5,6].

AI is poised to revolutionize many fields, including dentistry, because it is developing so quickly. Increased computing power, easier access to international information, and the availability of big data in the healthcare industry ready for AI processing are some of the factors propelling this development. In social life as well as dentistry, phrases like "digital transformations," "digitalized workflows," and "technical developments" are commonly employed [7]. In essence, the goal of AI research is to use computers and software algorithms to mimic human cognitive processes to tackle difficult issues and activities that are typically handled by human minds [8,9].

With disciplines like symbolic AI and machine learning, artificial intelligence (AI) is a subset of computer science or computer engineering. Machine learning, a subfield of artificial intelligence, uses algorithms to learn from experience and make better decisions or predictions without explicit instructions [10]. Sample data is needed for these kinds of calculations. Large-scale data processing is required to improve accuracy while preparing datasets for AI, which takes a lot of time and expertise from experts. Subfields such as statistical learning and deep learning are included in machine learning.

Without the need for manual rules or prior knowledge, machine learning (ML) allows systems to learn and carry out intelligent activities like finding patterns in massive datasets without human interaction. In order to optimize adjustable functions during this learning process, targets must be created and attained. A machine learning algorithm is trained by exposing it to random samples, finding patterns in them, and then applying those patterns to fresh data by progressively changing its parameters until it finds the right response. ML is comparable to an adult repeatedly exposing a toddler to photographs of cats in order to teach them to recognize them [11].

The goal of deep learning, a branch of machine learning, is to build a hierarchy of interconnected models. An easy-to-use, "shallow" system lacks the power of this multi-layered, "deep" system. When a child learns to identify a cat, for instance, they first identify basic features like the ears, nose, and eyes. They then combine these shapes to make larger groups like the head, trunk, and legs, which together constitute the entire cat [12].

Technological developments in computers have stimulated interest in and study of artificial intelligence (AI). This has facilitated scientific investigations and the perception of neuropsychological and psychological behaviors in three dimensions, which is particularly useful for understanding the brain. Methods such as magnetic resonance imaging, which captures abrupt metabolic activity in brain tissue, enable the study of particular mental processes and make a substantial contribution to our comprehension of brain mechanics. These insights into brain activity will be useful for developing AI in the future [13,14].

Dentistry is a highly tech-dependent sector, thus technological developments and AI integration are welcomed. Widespread AI applications in dentistry have been observed in recent years, encompassing robotic surgery, pathology detection, caries diagnostics, and dental implant installation [15-21].

AI's place in radiology has been further highlighted by the field's interoperability with image processing techniques in dental radiology. AI is used in several research projects to analyze 2D and 3D radiographic images for purposes such as diagnosing disorders like osteoporosis from jaw X-rays, identifying risk groups, automatically labeling anatomical structures, and detecting gingival diseases [22].

Rapid breakthroughs in AI are expected to change many industries, including dentistry. The present manuscript reviews the applications of AI in dentistry, both current and future, explores ways to enhance oral and dental health, and considers the potential educational and economic benefits of AI.

## Discussion

Artificial Intelligence (AI) is revolutionizing the field of dentistry, offering a range of benefits that enhance diagnostic accuracy, treatment planning, and overall practice management. This discussion explores the multifaceted impact of AI in dentistry, highlighting its role in improving diagnostic imaging, facilitating personalized treatment plans, expanding access to care, and optimizing practice management. By leveraging advanced AI technologies, dental professionals can provide more efficient, accurate, and patient-centered care, ultimately transforming the landscape of dental healthcare.

**Diagnostic Imaging and Improved Diagnostic Accuracy:** AI enhances dental diagnostic imaging by correctly interpreting CBCT images and radiographs. AI algorithms can identify diseases early and assist with treatment planning by spotting issues such as cavities, fractures, and tumors. Technologies like computer-aided detection (CAD) systems carefully analyze dental images, speeding up diagnosis and allowing for early interventions that lead to better patient outcomes [23-26].

**Enhanced Treatment Planning and Simulation:** AI software assists dental surgeons in planning treatments by simulating procedures like orthodontic adjustments and dental implants. It uses patient data to optimize outcomes and predict complications, facilitating personalized treatment plans for better results [27,28].

**Transforming Dental Practices, Expanding Access, and Elevating Patient Care:** AI technologies improve workflow management in dentistry by automating administrative tasks like appointment scheduling and patient record management, allowing more time for patient care. Virtual consultations and tele-dentistry services, supported by AI chatbots and assistants, provide remote dental advice and triage patients, increasing accessibility to care, especially in underserved areas [29,30].

**Predictive Analytics and Risk Assessment:** AI algorithms assess patient data, including medical history, habits, and genetic predispositions, to evaluate the risk of developing oral diseases like periodontitis or caries. This allows dental surgeons to implement personalized preventive measures and interventions for high-risk individuals, reducing the risk of disease progression [31,32].

**Improving Practice Management:** AI transforms practice management by automating administrative tasks, optimizing workflows, and enhancing operational efficiency. It analyzes patient demographics, financial data, and scheduling patterns to streamline operations, reduce overhead costs, and optimize resource allocation [33,34].

**Robot-Assisted Dentistry:** Combining robotics with AI can automate certain dental procedures, such as tooth cleaning or preparation for restorations. Robot-assisted systems enhance precision, reduce procedural errors, and minimize patient discomfort, thereby improving the overall patient experience [35].

**Cost Savings and Resource Optimization:** By optimizing workflows and reducing the need for manual intervention, AI enables dental practices to operate more efficiently, leading to cost savings and better resource utilization [36].

In general dentistry, AI-powered tools assist in detecting cavities, gum diseases, and oral cancers early through image analysis. Orthodontics benefits from AI through precise treatment simulations and custom aligner fabrication. In endodontics, AI helps in identifying root canal anatomy and predicting treatment outcomes. Prosthodontics utilizes AI for designing crowns, bridges, and dentures with improved fit and aesthetics. Periodontics sees advancements in monitoring periodontal health and predicting disease progression. AI also plays a role in oral and maxillofacial surgery by aiding in surgical planning and risk assessment. Overall, AI integration enhances efficiency, accuracy, and patient outcomes across various dental specialties.

## Periodontics

The study, diagnosis, and treatment of disorders affecting the soft and hard structures that support teeth are the focus of the dental specialty of periodontology. In this sector, periodontitis is one of the most common dental diseases that can cause tooth loss, tooth mobility, and loss of alveolar bone. Periodontal tissues are usually examined clinically and radiographically to diagnose periodontitis. However, even for skilled dental surgeons, identifying and interpreting periodontal bone loss (PBL) on radiographs can be difficult because of their low resolution and complicated structure. As a result, using AI to automatically aid in the processing of dental radiography images may make PBL evaluations more accurate and dependable [37-39].

Lin and colleagues [40] created a computer-aided diagnostic model that uses a hybrid feature engineering technique to measure the degree of PBL. These studies' positive results show that AI models perform on par with or even better than human analysis of PBL when applied for several tasks such as identifying PBL, classifying peri-implant diseases and disorders, and classifying periodontal problems [41,42].

Microbiological dental plaque on tooth surfaces is a major contributor to the development of periodontal disorders and is the main cause of gingivitis. A CNN algorithm was created in one study to categorize intraoral photos captured using a Quantitative Light-induced Fluorescence (QLF) camera in terms of the quantity of microbiological dental plaque [43]. The model performed well on the training set; however, it did not perform as well on the test set. In manual QLF analyses, dental surgeons reported significant intra- and interobserver agreement. However, when handling a large number of pictures, the CNN model was found to be more cost-effective and time-efficient [44,45].

## Prosthodontics

The area of dentistry known as prosthodontics is dedicated to employing the right prosthetic materials to restore lost function and aesthetics in cases of functional and aesthetic losses caused by deficits in teeth and the surrounding supporting tissues. Prosthetic restoration construction and preparation require a number of very precise procedures that can be carried out with conventional or digital techniques. CAD/CAM, or computer-aided design/computer-aided manufacturing, is one method that has gained popularity recently. It uses computer expertise to design and create materials required for prosthetic therapy [46].

A key component of CAD/CAM system optimization is intelligent software. According to a study, a unique soft computing optimization method could improve businesses' efficiency in maximizing machine parameters for industrial processes and drastically lower the expenses related to setting up and modifying machine operations [47]. Artificial intelligence (AI) applications in prosthesis creation help dental surgeons create the most aesthetically pleasing and functional prostheses by taking into account various criteria, including patient expectations, facial measurements, and anthropological calculations [48]. However, positioning mistakes, cementation errors, and occlusal correction errors with an abutment might arise when typical CAD/CAM technologies are applied to implant prosthesis cementation [49]. Using an AI model to manufacture zirconia implants for posterior teeth resulted in a 91% survival rate and a 93% success rate, according to a study that sought to eliminate these errors and save time [50].

In a different study, a CNN model created for the segmentation of tooth preparations automatically extracted the margin line with a 97.43% accuracy rate after learning the features of the margin line region [51].

Furthermore, results were obtained with an acceptable level of accuracy using an AI algorithm designed to create a dental prosthesis for a single molar that replicates the morphology of a real, healthy tooth. The study showed that AI could be used to create dental prostheses for single molars and stressed that more algorithm optimization and training could improve the accuracy of biomimetic AI-designed dental prostheses [52,53].

Advancements in AI applications have the potential to self-create novel dental restorations that adhere to the strictest requirements for fit, function, and aesthetics. These discoveries will greatly impact the field of orofacial and craniofacial prostheses as well.

## Oral Implantology

Treatment outcomes are improved by the use of AI techniques like deep learning, which enhance implant identification and peri-implantitis detection [54,55].

Among the most popular ways to treat tooth deficits are dental implants. Despite their high success rate, biological and mechanical problems can arise. Based on variables such as implant diameter, length, and cross-sectional area, eight distinct dental implant systems were categorized using machine learning in a 1996 study [56]. CNNs have recently been applied to the classification of various implant systems [57] demonstrating a significant degree of efficacy in differentiating between implant types with similar geometries in dental radiography pictures [58,59]. The success of implant surgery depends critically on the quality of the bone region available for insertion. An algorithm was able to predict trabecular bone quality with twice the accuracy of an experienced dental surgeon, according to a study that used CBCT scans to classify the condition of the bone. Despite some drawbacks, including the inconsistent distribution of groups in the dataset and the absence of a gold standard for group classification, the study advanced computer-aided design and manufacturing of implant-based prostheses [60].

## Forensic Dentistry

Age and gender determination from skeletal remains is essential for identification and forensic investigations in forensic dentistry [61]. Teeth are important in these processes because they are strong and resilient to damage [62]. The precision and effectiveness of these techniques have increased with the latest developments in AI and machine learning [63]. An overview of AI's present state in forensic dentistry is provided below:

### Age and Gender Estimation

- Neural Networks for Gender Determination: Studies have shown that neural networks can achieve high accuracy in distinguishing gender from anthropological skulls, with one study reporting 95% accuracy [64].
- Skeletal Age Calculation: Trained neural networks have also demonstrated success in estimating skeletal age from hand-wrist X-rays, with studies indicating strong performance [65,66].

**Digital X-Ray Analysis:** Accuracy in Age and Gender Estimation: A study using 1,142 digital X-ray images achieved 96% accuracy in age and gender estimation. The images were split between training and testing datasets, highlighting the potential of AI in forensic radiographic analysis [67].

**Root Length for Age Determination:** Deep Learning Models: Patil et al. explored the use of root length in age determination, finding that deep learning models outperformed traditional machine learning methods. Specifically, the mesial root length of the right third molar tooth was identified as a reliable age indicator. Expanding the training dataset with diverse radiographs is recommended for further refinement and clinical application [68].

## Additional Forensic Applications

**Bite Mark Analysis and Mandible Morphology:** AI algorithms are also being used to analyze bite marks and predict mandible morphology, demonstrating their versatility in forensic investigations [69,70].

## Current and Future Prospects

**Integration and Validation:** While AI shows promise in forensic dentistry, continuous research and validation are needed to ensure accuracy and reliability. Expanding datasets and refining algorithms will improve their effectiveness and clinical utility [71].

In summary, AI technologies are significantly advancing forensic dentistry by improving age and gender estimation, analyzing root lengths, and aiding in bite mark and mandible morphology analysis. These advancements are expected to enhance forensic identification processes and provide valuable tools for forensic experts.

## Oral Medicine and Pathology

Artificial Intelligence (AI) applications in oral pathology are revolutionizing the field by improving diagnostic accuracy and patient care in several ways:

**Diagnosing Odontogenic Cystic Lesions:** AI systems, particularly those utilizing machine learning and deep learning techniques, can analyze imaging data to identify and diagnose various odontogenic cystic lesions. These lesions, which originate from tooth-forming tissues, can be challenging to diagnose due to their diverse appearances and similarities with other pathologies. AI tools can assist oral pathologists by providing consistent and accurate interpretations of imaging data, thus reducing diagnostic errors and facilitating timely treatment [72].

**Predicting Tumor Margin Positivity:** For oral cancer, accurately determining the tumor margins is crucial for effective surgical treatment. AI applications can analyze histopathological images to predict tumor margin positivity, which refers to the presence of cancer cells at the edges of the removed tissue. By accurately predicting these margins, AI helps surgeons ensure complete removal of the tumor, reducing the likelihood of recurrence and improving patient outcomes [72].

**Predicting Survival Outcomes for Oral Cancer:** AI can also play a significant role in predicting survival outcomes for patients with oral cancer. By integrating various data sources such as patient demographics, clinical features, genetic information, and treatment responses, AI algorithms can generate predictive models that estimate a patient's survival probability. These models help clinicians tailor treatment plans to individual patients, optimize therapeutic strategies, and provide personalized care [73].

Overall, the integration of AI in oral pathology enhances diagnostic accuracy and patient care by providing advanced tools for the detection, analysis, and prediction of various oral pathologies. This leads to more informed clinical decisions, improved treatment outcomes, and ultimately, better patient care.

## Oral Radiology

Dentistry makes connections between clinical, systemic, and radiological evidence to investigate diseases and disorders of the mouth, teeth, and jaws. Digital radiography images, the patient's anamnesis and complaint history, and, if required, intraoral/extraoral photographs are all documented. These tools are frequently used to evaluate oral disorders such as tumors, cysts, inflammatory conditions, gingival diseases, and dental caries [74,75].

Computational language can be readily converted into digital radiographs, which are radiographic pictures created by X-ray irradiation and digitally encoded. Artificial intelligence (AI) in radiology has advanced faster as a result of the digitization of radiographs. During ordinary dental practice, dental radiography—which includes intraoral radiographs, panoramic, cephalometric, and sophisticated imaging techniques including cone beam computed tomography (CBCT)—is gathered for the purposes of diagnosis, treatment planning, and treatment evaluation. These enormous databases provide an abundance of information for research in science and medicine, particularly when it comes to AI development [75,76].

In the practice of radiology, radiologists visually assess and interpret results based on the features of the images. But this evaluation is frequently laborious and subjective. Contrarily, AI techniques offer quantitative analysis and automatic identification of intricate patterns in imaging data, which makes them useful instruments for assisting medical professionals in providing more impartial and consistent evaluations of radiological pictures [77,78].

When interpreting radiographs, dental surgeons first identify and differentiate between radiological features of diseases and normal tissues. Based on the overlap of obtained radiographic information with clinical observations, they then make preliminary and differential diagnoses. In essence, this process of discrimination and recognition is a pattern recognition function. Some radiography analyses may now be performed automatically by computers thanks to machine learning techniques that enable them to recognize patterns. However, existing machine learning approaches cannot yet justify the outputs obtained in the radiography interpretation process [79-82].

Applications of AI in dentomaxillofacial radiology appear to be quite promising. Algorithms for picture classification, detection, segmentation, recording production, and augmentation have been the main focus of recent research. The main goals of the AI-based algorithms created in this sector are picture analysis, diagnosis, and quality improvement. Accurate results require a vast quantity of data, and the creation of accurate and consistent datasets requires the involvement of skilled radiologists [83,84].

Radiographs can be used to identify structures, separate (segment), or categorize desired data from other data in the picture using artificial learning models. Figures that depict the classification, segmentation, and lesion identification on periapical radiographs schematically depict these applications. Dental caries, periodontal diseases, vertical root fractures, periapical pathologies, osteosclerosis, odontogenic cysts and tumors, maxillary sinus pathologies, and the identification of temporomandibular joint diseases are a few examples of AI applications in dentomaxillofacial radiology [85-87].

The most used radiological diagnostic technique in this sector is the panoramic radiograph, which images the mandible and maxilla jaw bones, all of the teeth that are currently in place, and the surrounding support tissues. Owing to the intricate anatomical structure, 2D presentation may result in superpositions, which could lead to inaccurate and lacking interpretations. In AI investigations, panoramic radiographs are becoming a valuable source of research data. Convolutional neural networks (CNNs), for instance, have been shown to diagnose benign tumors in the jaws on panoramic radiographs with diagnostic accuracy comparable to that of specialist dental surgeons. In contrast to specialized dental surgeons, an algorithm developed in another study using the identical 2D panoramic radiographs was able to identify osteoporosis with good accuracy [88].

With sensitivity, accuracy, and F-measure values of 0.88, 0.83, and 0.86, respectively, an AI system designed to identify idiopathic osteosclerosis (IO) in panoramic radiographs demonstrated excellent results, suggesting the possibility to reliably identify IOs in these images [89].

When 2D radiographs and clinical evaluation are not enough for 3D imaging, CBCT is frequently performed. AI algorithms were used in a study to detect periapical lesions with 92.8% accuracy. The program was also able to detect and number teeth in volumetric data [90].

In dentistry, radiographic imaging is essential for both diagnosis and diagnosis-based treatment planning. Radiography images are analyzed as part of treatment planning in cases like implant planning, orthognathic surgery, and other surgical applications. The advancement of AI in several fields is extremely beneficial. Dentomaxillofacial radiologists continue to be key players in AI research because they comprehend the fundamentals and features of radiographic imaging and are skilled in interpreting radiographs for a variety of disorders. Given the growing amount of medical data in radiology practice, AI-detected data will lessen the number of incorrect and incomplete diagnoses as well as the daily burden for dental surgeons [91].

## Pedodontics and Preventive Dentistry

AI and machine learning are advancing pediatric dentistry by helping to identify, treat, and manage children's oral health problems. An overview of current advancements and uses is shown below:

**Assessment of Oral Health:** Machine Learning Algorithms: Researchers have developed algorithms to assess children's oral health status and treatment needs using data from questionnaires completed by children and their parents. This approach has potential for screening purposes, such as in schools, and aims to streamline the assessment process [92,93].

## Pain Management

**AI in Anesthesia:** AI models have been developed to predict individual pain levels and analgesia responses for postoperative pain management. This application aims to improve pain management strategies by tailoring them to individual needs [94,95].

## Communication Tools

**Assistive Tools:** AI-driven assistive tools have been designed to help children and individuals with disabilities communicate their pain and needs more effectively. These tools facilitate better communication in populations that have difficulty expressing themselves [96,97].

## Molar-Incisor Hypomineralization (MIH)

**Detection and Classification:** The European Academy of Pediatric Dentistry (EAPD) has focused on MIH, a condition affecting the enamel of molars and incisors. A deep learning-based convolutional neural network (CNN) was developed to detect and classify teeth affected by MIH in intraoral photographs, achieving an overall diagnostic accuracy of 95.2% [98-100].

## Dental Plaque Detection

**AI for Plaque Detection:** AI models have been used to detect dental plaque in primary teeth from intraoral photographs. These models have shown clinically acceptable performance, comparable to experienced pediatric dental surgeons, in diagnosing dental plaque [101].

## Detection of Permanent Tooth Germs

**Deep Learning in Radiographs:** A study using 4,518 panoramic radiographs of children aged 5-13 applied a deep learning-based approach with the YOLOv4 model to detect permanent tooth germs. The model achieved an average precision of 94.16% and an F1 value of 0.90. This technology aids in the early diagnosis of missing or supernumerary teeth, facilitating accurate treatment planning [102].

## Current and Future Prospects

**Early Diagnosis and Treatment Planning:** AI technologies, particularly those utilizing deep learning and convolutional neural networks, are proving valuable in early diagnosis and treatment planning for various pediatric dental conditions. These advancements are expected to improve diagnostic accuracy, streamline workflows, and enhance patient care [103].

**Integration and Validation:** For AI tools to be widely adopted in clinical practice, they must be thoroughly validated through larger studies and integrated into existing workflows. Continued research and development are crucial to refine these technologies and ensure their effectiveness and reliability [104,105].

In summary, AI is transforming pediatric dentistry by providing advanced tools for diagnosing and managing oral health issues in children. These developments promise to enhance clinical outcomes, improve patient communication, and optimize treatment planning.

## Orthodontics

The area of dentistry known as orthodontics is responsible for identifying and treating abnormalities in tooth positioning as well as problems with the growth and alignment of the jaws.106 AI is being increasingly used in orthodontics to enhance treatment planning and diagnostic precision.

**Modeling Extraction Requirements Before Orthodontic Treatment:** An artificial neural network was used to model the extraction requirements before orthodontic treatment. The study concluded that the accuracy of predicting extraction needs significantly increased, especially when a decision-making model with pretraining was used [107].

**Estimating Mesiodistal Widths of Unerupted Teeth:** The prediction of mesiodistal widths of unerupted teeth using a deep learning (DL) model was compared to the traditional Moyers table (MT). The DL system achieved an accuracy of 49.5% for predicting the widths of unerupted mandibular canine and premolar teeth, suggesting that AI models may offer a potential alternative to existing methods in estimating tooth size and providing diagnostic support for mixed dentition analysis [108].

**Cephalometric Image Analysis:** Cephalometric image analysis is widely used in orthodontics to evaluate the skeletal anatomy of the human skull, aiding in treatment planning and the evaluation of treatment outcomes. Traditionally, many anatomical landmarks need to be defined manually, which is time-consuming. AI technology has been developed to automate the identification of cephalometric anatomical points and classify skeletal relationships, thereby reducing the clinician's burden and saving time. AI models have advanced to not only identify anatomical points but also measure and analyze these points in cephalograms. A 2015 study using knowledge-based algorithms developed an AI model capable of automatic cephalometric measurement. The study found no significant difference between the AI-based automatic measurements and manual measurements, highlighting the potential of AI in cephalometric orthodontic diagnostics [109].

**Sella Turcica Segmentation and Classification:** A recent CNN-based AI study focused on the segmentation and classification of the Sella Turcica using CBCT images. This study yielded highly accurate results, indicating that AI algorithms can significantly aid in the detection of anatomical landmarks important for orthodontic diagnosis. This advancement is expected to save orthodontists time and facilitate more accurate diagnoses [110].

In summary, the integration of AI in orthodontics is showing great promise in enhancing diagnostic accuracy, improving treatment planning, and reducing the workload of orthodontic professionals. As AI technology continues to evolve, its applications in orthodontics and other dental fields are likely to expand, offering more efficient and effective tools for dental care.

## Oral Surgery

Treatment and rehabilitation of pathological disorders, injuries, and developmental abnormalities of the mouth, teeth, and jaws are provided by the dental specialty of oral and maxillofacial surgery. In this discipline, the extraction of impacted third molars is among the most frequently performed surgical procedures. Following third molar surgery, facial swelling is a common postoperative consequence. An artificial neural network model was created in a study to forecast the likelihood of facial edema after extraction. Surgical considerations included the patient's age, gender, health and dental status, the third molar's relationship to the ramus and second molar, the type of incision used, the degree of impaction, whether the tooth was removed in one piece or in several, and the length of the treatment. A surgeon performed 400 extractions; 300 patient data were used for testing and 100 for model training. The model's prediction accuracy for swelling was 98% [111].

Convolutional neural networks (CNNs) are being used in oral and maxillofacial surgery research to automatically identify mandible fractures on panoramic radiographs. In one study, F1 scores ranged from 0.6 to 0.87 and were used to identify and categorize mandible fractures (such as condyle, coronoid, and ramus) on panoramic radiographs. Detecting condyle fractures had the highest sensitivity, while coronoid fractures had the lowest [112,113].

For dental surgeons, diagnosing and treating disorders of the temporomandibular joint (TMJ) is one of the most challenging problems. The goal of a study was to use the results of the TMJ clinical examination to build an artificial neural network model that could differentiate between internal anomalies in the TMJ and normal joints. With sensitivity and specificity ranging from 37% to 100%, the model was trained and evaluated to detect unilateral or bilateral anterior disc displacements with and without reduction. Another study identified the DenseNet169 and InceptionV3 models as the top performers and suggested a novel diagnostic method to accurately diagnose TMJ disc displacement using AI. They emphasized that to fully validate their system, larger studies utilizing data from other institutions or countries are required. The use of deep learning neural networks in automatically detecting TMJ disc displacement from sagittal MRI images shows promise in assisting radiologists [114,115].

Another recent study found that the AI model performed similarly to specialized physicians in MRI condyle, articular eminence, and disc segmentation. The study also suggested that doctors could find it useful to use CNN-based segmentation models to help them identify the fundamental anatomy seen in TMJ MRIs. Using an AI method to locate the articular disc and surrounding structures automatically could reduce time and increase the accuracy of TMJ MRI interpretation [116].

Robotic systems are increasingly used in everyday medical and life sciences applications, such as minimally invasive heart valve repair and gynecological operations. AI techniques are used by autonomous robots to plan and carry out specific tasks independently. Although implant surgery is progressing towards complete automation of implantology, the scarcity of research on this subject means that these techniques are not yet widely applied due to the lack of satisfactory accuracy and reliability outcomes [117].

AI applications are also benefiting the field of orthognathic surgery, which is a subspecialty of oral and maxillofacial surgery. Digital imaging in orthognathia has undergone significant changes due to the increasing use of intraoral scanners. AI applications in orthognathic surgery can enhance maxillofacial imaging, treatment planning, customized orthodontic and surgical equipment, and treatment follow-up [118].

It is projected that, in light of these advancements, the application of AI in surgery will continue to grow and improve over time.

## Diagnosis, Caries, and Endodontics

The diagnosis and treatment of pulpal and periapical diseases is the focus of the dental specialty known as endodontics, which also includes the study of root canal anatomy, shaping methods, and treatment materials [119,120]. In endodontics, artificial intelligence (AI) is being increasingly used to improve treatment planning and diagnostic precision. Here is how AI is being applied in this field:

### Imaging and Morphology Assessment

**Panoramic Radiographs:** Traditional 2D panoramic radiographs may be insufficient for understanding root canal morphology. AI-based methods have been developed to estimate the number of distal roots in mandibular first molars. A study using two separate convolutional neural network (CNN) algorithms found both models had high accuracy in discriminating accessory roots, suggesting AI can effectively analyze complex root canal structures from panoramic images [121,122].

## Canal Orifice Detection

**Location and Classification:** Identifying root canal openings is crucial for successful treatment. AI models have been developed to locate and classify canal orifices with high accuracy. A study reported that an AI model detected canal orifices with 94% accuracy and differentiated between upper and lower molars with 90% accuracy, indicating that AI can aid in real-time detection and classification of canal orifices [123,124].

## Determining Working Length

**AI in Working Length Measurement:** The determination of the working length of a canal is a critical step in root canal treatment. An AI-based approach was explored to reduce errors in measuring canal working length using radiographs. In a study where extracted teeth were placed in cadaver sockets, AI models trained with detailed images achieved reliable measurements of the canal file position. This suggests that AI can enhance the accuracy of working length determination [125,126].

**Comparison with Traditional Methods:** Traditional methods to assess working length include radiography, digital tactile sense, electronic apex locators, and CBCT imaging. The clarity and interpretation of digital radiographic images are vital for accurate assessments. A study comparing AI to traditional methods found that AI, particularly neural networks, provided more accurate working length measurements than endodontists' manual determinations using a stereomicroscope as the gold standard [127,128].

## Challenges and Limitations

**Image Quality and Interpretation:** Accurate interpretation of root canal anatomy relies on high-quality images. Misdiagnoses can occur due to poor image clarity or other factors affecting radiographic interpretation. AI models can potentially mitigate these issues by providing more consistent and objective analyses [129,130].

In summary, AI is proving to be a valuable tool in endodontics by enhancing the precision of diagnostics and treatment planning. Its applications range from improving the accuracy of root canal morphology analysis and canal orifice detection to refining the measurement of working length, thereby supporting better clinical outcomes in endodontic procedures.

## Restorative and Esthetic Dentistry

AI has significantly improved the detection, diagnosis, and treatment of dental caries and related diseases in restorative and aesthetic dentistry. Here is a thorough rundown of how AI is being used in these fields:

## Radiological Examination and AI

**Detection of Dental Caries:** Radiological examinations, including periapical, bitewing, and panoramic radiographs, are crucial for diagnosing dental caries, especially those not visible clinically. AI, particularly deep learning (DL) models and convolutional neural networks (CNNs), has shown promise in enhancing the accuracy of caries detection on radiographs. Studies have reported high performance in classifying dental caries, with accuracy ranging from 86% to 97% [131-133].

**Overcoming Image Quality Issues:** AI helps mitigate challenges such as noise, artifacts, and low contrast in radiographic images that can obscure caries detection. By leveraging advanced algorithms, AI models can identify and classify pathologies more reliably than traditional methods [134].

## Detection on Different Surfaces

**Occlusal Caries Detection:** Caries on occlusal surfaces can be challenging to detect using radiographs due to high enamel density, which may obscure early demineralization. AI models have been developed to address this issue by analyzing intraoral photographs. For instance, a deep learning model designed for diagnosing occlusal caries from intraoral camera images used data augmentation and transfer learning to improve its performance, given the typically small dataset of in vivo photographs [135].

**Transillumination Method:** Transillumination, which involves shining light through teeth to detect carious lesions, has been explored using CNN algorithms. While the designed CNN showed potential, sensitivity and specificity tests suggested that it may not yet be fully reliable for clinical practice [136].

## AI in Caries Management

**Predictive Modeling:** AI can also assist in predicting the progression of carious lesions, helping dental surgeons plan appropriate treatment strategies. By analyzing historical data and imaging results, AI models can forecast the likelihood of caries advancement and the need for intervention [137].

**Integration with Other Diagnostic Tools:** AI can be integrated with other diagnostic methods, such as digital intraoral cameras and fluorescence-based systems, to provide a comprehensive diagnostic approach. This integration allows for more accurate and timely detection of carious lesions [138].

## Advantages and Challenges

### Advantages

**Enhanced Accuracy:** AI algorithms improve diagnostic accuracy by reducing human error and providing consistent assessments.

**Efficiency:** Automation of caries detection speeds up the diagnostic process and allows for more efficient use of radiographic and photographic data.

**Data Augmentation:** Techniques like data augmentation and transfer learning help improve the performance of AI models, especially in scenarios with limited data.

### Challenges

**Data Quality:** The accuracy of AI models heavily depends on the quality of the training data. Poor-quality or biased data can affect the model's performance.

**Clinical Integration:** While AI shows promise, its integration into routine clinical practice requires validation through larger, multi-center studies and further development to ensure reliability and ease of use.

## Future Prospects

**Continued Research:** Ongoing research aims to refine AI algorithms and enhance their ability to detect and diagnose various forms of dental caries. Advances in imaging technology and AI methodologies will likely lead to more effective diagnostic tools.

**Clinical Implementation:** As AI models become more validated and reliable, they are expected to become integral components of diagnostic workflows in restorative and aesthetic dentistry. This will facilitate earlier detection of carious lesions and improve overall patient care.

In summary, AI is transforming the field of restorative and aesthetic dentistry by enhancing the detection and diagnosis of dental caries through advanced imaging and analysis techniques. While challenges remain, continued research and development are likely to improve the accuracy and clinical applicability of these technologies.

## Public Health Dentistry

AI-driven virtual dental assistants are transforming the dental care landscape by excelling in various aspects, including diagnosis, appointment management, and health risk identification. Their applications extend beyond individual patient care to public health surveillance and personalized health advice [139,140].

**Diagnosis:** AI-driven virtual dental assistants can analyze patient data, including symptoms, medical history, and diagnostic images, to provide preliminary diagnoses. These systems use machine learning algorithms trained on vast datasets to identify patterns and suggest potential conditions. By doing so, they support dental professionals in making accurate and timely diagnoses, potentially catching issues that might be overlooked during a traditional examination.

**Appointment Management:** Virtual dental assistants streamline the appointment scheduling process by efficiently managing calendars, sending reminders to patients, and handling cancellations or rescheduling. They can also use patient data to predict and suggest optimal times for follow-up visits, ensuring that patients receive timely care and reducing the likelihood of missed appointments.

**Health Risk Identification:** AI systems can evaluate patient data to identify potential health risks, such as susceptibility to periodontal disease or oral cancer. By continuously monitoring and analyzing health indicators, these virtual assistants provide early warnings and suggest preventive measures, contributing to better long-term oral health outcomes.

**Public Health Surveillance:** On a larger scale, AI-driven virtual dental assistants can aggregate and analyze data from numerous patients to identify trends and patterns in oral health. This information is invaluable for public health surveillance, allowing health authorities to track the prevalence of diseases, identify emerging health threats, and allocate resources effectively. It also helps in formulating public health policies and interventions to improve community oral health.

**Personalized Health Advice:** These virtual assistants offer personalized health advice based on individual patient data. By considering factors such as age, medical history, lifestyle, and genetic predispositions, AI systems provide tailored recommendations for oral hygiene practices, dietary adjustments, and preventive care. This personalized approach enhances patient engagement and adherence to health advice, leading to better overall health outcomes.

Overall, AI-driven virtual dental assistants enhance the efficiency and effectiveness of dental care by providing advanced diagnostic support, improving appointment management, identifying health risks, aiding in public health efforts, and offering personalized health advice. This technological integration is instrumental in advancing dental practice and improving patient care on multiple levels.

## AI in Dental Education

Artificial Intelligence (AI) technologies in dentistry are revolutionizing the conventional learning environment and enhancing training results [141,142]. Below is an outline of how AI is affecting clinical training and dental education:

### Intelligent Teaching Systems

**Simulation and Virtual Patients:** AI-driven simulations and virtual patient scenarios provide dental students with opportunities to practice clinical skills in a risk-free environment. These systems offer feedback on performance, helping students learn more effectively than traditional methods. Studies indicate that students using these systems achieve competency levels faster.

**Enhanced Feedback Mechanisms:** Virtual patients can offer detailed feedback, allowing students to evaluate their work against ideal scenarios. This enhances learning by providing immediate and relevant information, which can accelerate skill development.

### Preclinical Training

**Traditional vs. Virtual Models:** In preclinical training, traditional phantom models used for skill development are being supplemented with AI-powered virtual patients. These systems provide more dynamic and realistic training experiences, leading to improved learning outcomes.

**Robotic Models:** Advanced robotic models are used in preclinical laboratories to simulate various dental functions, such as verbalizing pain, head movements, and fluid simulations (e.g., bleeding and saliva flow). These models help students develop basic motor skills and enhance their clinical training.

### Clinical Decision Support Systems

**Error Reduction and Decision-Making:** AI-driven clinical decision support systems are valuable tools that assist dental surgeons in making better medical decisions and reducing clinical errors. These systems are especially useful for inexperienced dental surgeons and students, as they provide guidance and support during the treatment process.

### Integration of AI in Curriculum

**Inclusion in Education:** Incorporating AI-based subjects into the dental curriculum is crucial. Understanding AI terminology and principles will prepare students to be both users and developers of AI applications in the future. This will help advance the field of dentistry and integrate cutting-edge technology into clinical practice.

### Future Directions

**Increased Use and Affordability:** As software and hardware costs for robotic and AI systems decrease, their use in dental education is expected to become more widespread. Ongoing research and development will continue to enhance these technologies, providing more opportunities for students and improving educational outcomes.

In summary, AI is significantly enhancing dental education by providing advanced simulation tools, improving feedback mechanisms, supporting clinical decision-making, and preparing students for future developments in the field. Integrating AI into the curriculum and utilizing advanced technologies will help shape the next generation of dental professionals and improve the overall quality of dental education.

## Challenges and Considerations

The integration of AI into dentistry presents several challenges related to data protection, legal control, ethical issues, bias, and interaction with existing systems. Here is a thorough examination of these issues:

### Data Privacy and Security

**Patient Data Collection:** AI systems in dentistry require extensive data collection, including sensitive patient information. Ensuring the privacy and security of this data is crucial.

**Regulatory Compliance:** Dental practitioners must adhere to regulations such as the Health Insurance Portability and Accountability Act (HIPAA) in the U.S. or General Data Protection Regulation (GDPR) in Europe. These regulations are designed to protect patient confidentiality and ensure that data is managed securely [143].

## Integration with Existing Systems

**Infrastructure and Training:** Integrating AI technologies into existing dental practice management systems may require significant investments in new infrastructure and training for staff. This can be a barrier to adoption for some practices [144].

**Compatibility and Scalability:** AI solutions must be compatible with existing systems and scalable to handle growing data and technological advancements. Ensuring smooth integration without disrupting workflows is essential for successful implementation.

## Ethical and Legal Implications

**Autonomous Decision-Making:** As AI systems become more autonomous, issues related to accountability and liability arise. Determining who is responsible for decisions made by AI systems is a critical concern [145].

**Patient Data Privacy and Algorithmic Biases:** Addressing ethical concerns regarding patient data privacy and biases in AI algorithms is vital. Biases in training data can lead to unequal treatment outcomes, so transparency and fairness in algorithm development are necessary [146].

## Bias and Fairness

**Algorithmic Biases:** AI algorithms can reflect biases present in their training data, potentially leading to disparities in diagnosis and treatment. It is important to identify and mitigate these biases to ensure fair and equitable treatment outcomes [147].

**Ensuring Fairness:** Continuous evaluation and updating of AI algorithms are required to minimize biases and promote fairness in AI-enabled services [148].

## Regulatory Oversight

**Regulatory Frameworks:** Developing robust regulatory frameworks is essential to safeguard patient safety and maintain the quality of care. Regulatory bodies should provide clear guidelines and oversight to ensure that AI applications adhere to professional standards [149].

## Future Directions

Hybrid Intelligence in Dentistry

## Concept and Application

**Definition:** Hybrid intelligence involves the synergy between human intelligence and artificial intelligence (AI) to leverage the strengths of both. It combines human intuition, experience, and judgment with the computational power and data analysis capabilities of AI [150].

**Multimodal Image Fusion:** One application of hybrid intelligence in dentistry is the development of advanced image fusion methods. By combining different types of images (e.g., radiographs, CBCT scans, intraoral photographs), clinicians can achieve more comprehensive diagnostic insights and make better-informed treatment plans.

## Diagnostic Performance and Generalizability

**Algorithm Variation:** The performance of AI models can vary based on the algorithms used. While many AI models show high success rates, it's crucial to validate their generalizability and reliability using diverse datasets from multiple institutions before clinical adoption.

**Validation:** Ensuring that AI models are tested on representative and diverse images helps confirm their effectiveness across different settings and populations.

## Role of AI in Dental Decision-Making

**Supporting Role:** AI and computer-based neural networks assist in decision-making and error reduction during dental treatment planning. However, their implementation requires ongoing research and application to refine and enhance their capabilities.

**Integration into Clinical Practice:** Dental surgeons need to stay updated with technological advancements and integrate AI tools into their practice. This collaboration between technology and clinicians is essential for advancing the field and improving patient outcomes.

## Challenges and Considerations

**Technical and Ethical Challenges:** AI faces both technical and ethical challenges, including data protection, security, and the delegation of critical medical decisions to machines. Addressing these concerns is crucial for the responsible development and application of AI in healthcare.

**Continuous Research:** The field of AI is evolving rapidly, and continuous research is needed to address these challenges and ensure that AI tools are safe, effective, and equitable.

## Future Outlook

**Revolutionizing Healthcare:** AI has the potential to revolutionize healthcare and dentistry by enhancing diagnostic accuracy, treatment planning, and patient management. Collaboration between dental surgeons and technology developers will accelerate progress and improve the utility of AI applications.

**Necessity of Cooperation:** The future of AI in dentistry will depend on the cooperation between dental surgeons and technologists. This partnership will drive innovation and ensure that advancements are practical and beneficial for clinical practice.

In conclusion, hybrid intelligence and AI have the potential to significantly advance the field of dentistry. By integrating AI with human expertise, the field can achieve better diagnostic accuracy, improved treatment planning, and enhanced patient care. Addressing the associated challenges through ongoing research and collaboration will be key to realizing the full potential of these technologies.

## Conclusion

Artificial Intelligence (AI) has the potential to revolutionize the dental field by enabling precise diagnosis, personalized treatment planning, and enhanced patient care. Its applications are diverse and beneficial for both professionals and patients, ranging from therapy simulation to diagnostic imaging. However, smooth integration requires careful attention to issues such as data privacy, ethical dilemmas, and legal frameworks. Responsible adoption of AI can ensure its efficacy and efficiency while making dental care more accessible.

AI facilitates precision dentistry tailored to individual needs, underscoring the continued importance of human qualities in the field, such as empathy, compassion, and commitment to patient care. As a game-changer in the broader healthcare landscape, AI enhances the accuracy of specialists, reduces human error, and paves the way for better smiles and longer lives.

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