Artificial intelligence in dentistry: current applications and future perspectives

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Artificial intelligence (AI) encompasses a broad spectrum of emerging technologies that continue to influence daily life. The evolution of AI makes the analysis of big data possible, which provides reliable information and improves the decision-making process. This article introduces the principles of AI and reviews the development of AI and how it is currently being used. AI technology has influenced the health care field because of the need for accurate diagnosis and superior patient care. In order to understand the trend of AI in dentistry, electronic searching was carried out, combined with approaching individual companies to obtain the details of AI-based services. The current applications of AI in clinical dentistry were introduced and summarized. In the future, the AI-based comprehensive care system is expected to establish high-quality patient care and innovative research and development, facilitating advanced decision support tools. The authors believe that an innovative inter-professional coordination among clinicians, researchers, and engineers will be the key to AI development in the field of dentistry. Despite the potential misinterpretations and the concern of patient privacy, AI will continue to connect with dentistry from a comprehensive perspective due to the need for precise treatment procedures and instant information exchange. Moreover, such developments will enable professionals to share health-related big data and deliver insights that improve patient care through hospitals, providers, researchers, and patients. *(Quintessence Int 2020;51:248–257; doi: 10.3290/j.qi.a43952)*

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Artificial intelligence (AI), first coined by John McCarthy,[1] refers to machines that can imitate human knowledge and behavior. This intelligent capability can be implemented by sequences of algorithms. With the improvement of computer hardware, it is possible for AI to process large datasets, computationally to reveal human behavior and and allow interaction with people. This technology qualitatively improves people's lives and continuously influences the world.

Machine learning is one of the AI fields that researchers and practitioners have applied broadly, using it for data analysis. Machine learning was first mentioned in 1959 by Arthur Samuel,[2] who defined it as a process that enables computers to learn without being explicitly programmed. Nowadays, machine learning has made it possible for a computer to classify or predict an outcome from an extensive database. This processing system was later significantly improved with the breakthrough of deep learning, which enabled the computer to process numerous algorithms effortlessly with graphics processing units (GPUs).

For example, Amazon Alexa (Amazon) was released as a virtual assistant, with the ability to recognize and understand different voices and accents. With the potential of adding "skills," it started helping people to complete their daily life tasks. AlphaGo (Google DeepMind) was programmed with deep learning, and it defeated several Go champions. In iPhone (Apple), the Apple A13 Bionic chip has been developed to handle the software demands of machine learning processes, such as the instant correction of low-light pictures. IBM Watson (IBM) was also introduced as an AI solution with the feature of cognitive computing. This self-learning system was designed to solve problems without human assistance in several professional fields. The purpose of this article is to review the current applications of AI in health care and dentistry. Additionally, the future perspectives of AI in the dental profession will be addressed.

Table 1 Summary of current (to 2018) artificial intelligence applications in clinical dentistry

	Publication year	Study	Detail	Artificial intelligence technology used
Radiology	2018	Lee et al[12]	Diagnosis of caries	Deep learning network (GoogLeNet Inception v3)
Orthodontics	2016	Jung and Kim[14]	Diagnosis of the need of orthodontic extraction	Artificial neural network
	2018	Thanathornwong[13]	AI clinical decision support	Bayesian networks
	2018	Patcas et al[15]	Treatment outcome analysis	Convolutional neural network
Periodontics	2018	Lee et al[16]	Diagnosis and prediction of periodontally compromised teeth	Convolutional neural network
	2018	Feres et al[17]	Differentiation between aggressive and chronic periodontitis	Support vector machine
Oral medicine	1995	Speight et al[18]	Risk assessment of oral cancer	Artificial neural network
	2018	Kim et al[19]	Prediction of MRONJ	Artificial neural network, support vector machine, logistic regression, and decision tree

MRONJ, medication-related osteonecrosis of the jaw.

AI application in health care

With the potential to "train" a computer program to achieve highly intelligent capabilities, AI began emerging in the health care fields. Patient care could be improved with AI, which is a better diagnostic aid and reduces errors in daily practice.

Medical image interpretation has developed from expert systems, through atlas-based models, to the future of deep learning.[3] The big data of digital radiographs can be used, as it has great potential to improve the diagnosis process in radiology with the aid of AI.[4] AI with deep learning could potentially assist medical radiology via automated data mining. New knowledge will be discovered with minimal human knowledge involvement. Wearable technology with the installation of intelligence applications can predict when a life-threatening crisis like a stroke may occur in a patient, giving clinicians the opportunity to provide effective, early interventions.

Electronic medical records and scientific databases can be analyzed in an efficient and applicable method using AI. The diagnosis of human congenital anomalies was improved with the emergence of big scientific data.[5] The support vector machine (SVM), a learning model of machine learning, has become a standard method of analysis in medical research. Complicated conditions such as traumatic brain injury can be classified with SVM.[6] In cardiovascular medicine, due to a need for precision in diagnosis and treatment, deep learning might play a critical role in its development. Identifying various cardiovascular diseases with high precision diagnosis would be possible with the implementation in deep learning.[7] In viral immune surveillance, utilizing AI to analyze viruses has improved translational research.[8] Using AI technology can fill gaps in knowledge and improve costs and benefits.

In disease management, AI has been widely utilized to analyze treatment outcomes or develop precision medicine. These innovative machine learning algorithms can be considered as a powerful analytic tool that allows clinicians to conceptualize and study mood. In a meta-analysis, it was concluded that the application of machine learning algorithms could predict therapeutic outcomes in treating depression with an overall accuracy of 82%.[9] In ophthalmology, AI could improve diagnoses and treatment options for many eye conditions including corneal ectasias, glaucoma, and age-related macular degeneration and diabetic retinopathy.[10]

Applications of AI in dentistry

AI in dentistry is a growing topic, as it benefits clinicians with high-quality patient-care, and simplifies complicated protocols by providing a predictable outcome. Its applications evolve rapidly day by day. In order to understand the trends of AI, electronic searching was carried out, combined with approaching individual companies to obtain the details of AI-based services. Electronic searches were explored using the following databases: PubMed, Scopus, and Google Scholar. The keywords used were "artificial intelligence," "AI," "machine learning," and "deep learning." The keywords "dentistry," "dental," and "dental

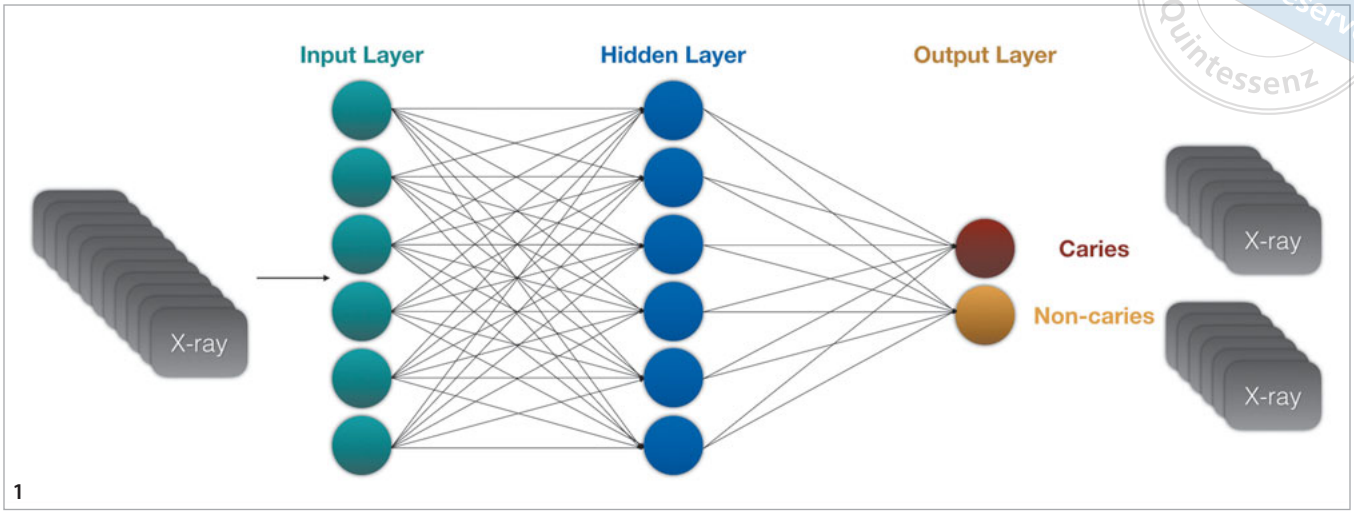


Fig 1 The example of deep learning with the application of detecting caries using radiographs. The radiographs will be imported to the software as the input layer. Through multiple "hidden layers," the algorithms will classify imported radiographs as "caries" or "non-caries" based on the AI training.

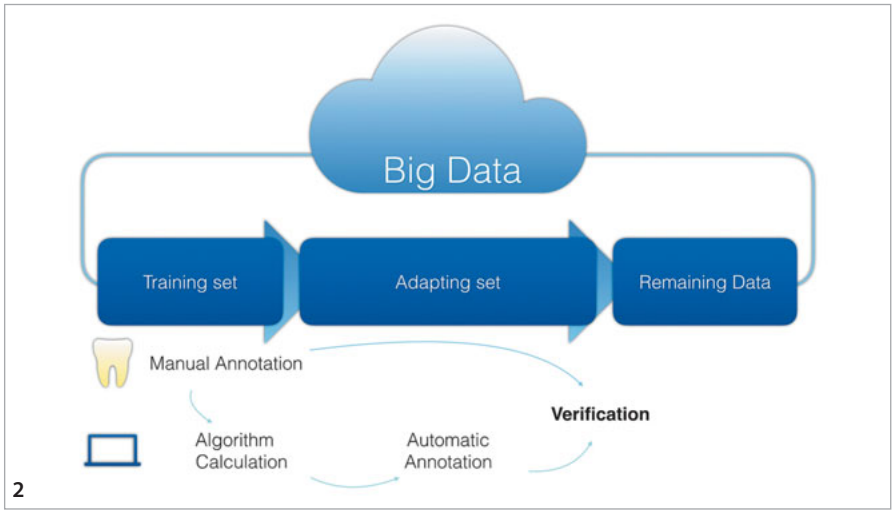


Fig 2 An example of AI training. The clinician (Tooth) manually annotated the anatomical landmarks in the training set from the big data. The engineer (Laptop) utilized algorithms to further continue the annotation automatically in the adapting set. The precision was verified during the training and was improved during the process. The remaining data can be calculated by AI after the AI training.

care," were used as conjunctive search terms. After reviewing and excluding the information, the applications of AI in clinical dentistry from scientific journals were summarized in Table 1.

AI has been used to improve image interpretation in dental radiology. In two-dimensional (2D) radiographs, digital radiographs consist of thousands of pixels. Each unit of the pixel represents different levels of brightness within the grid. The pixel presenting radiopacity can be identified as metal or as a structure with higher density. Using these characteristics, AI programs "learn" to analyze the digital image. For example, digital radiographs can be calculated using the algorithms through input layers, hidden layers, and output layers to detect caries (Fig 1). This process of AI training relies on the coordination of the software engineer and the clinical expert (Fig 2). With a large number of dental radiographs, the clinical expert analyzes a certain number of radiographs as a training set. The experienced clinician manually annotates anatomical landmarks, while the software engineer utilizes the training set and architects the learning model to teach the AI the skill of predicting the remaining information as an adapting set. Both clinicians and engineers will verify the precision of the adapting set. The coordination of these AI trainers expands the capacity of the software.

In a recent paper, the potential applications for using AI to identify interproximal caries using a series of bitewing radio-

Table 2 Current applications of artificial intelligence-based dental software (if applicable) or services introduced by dental companies (some services may still be under development)

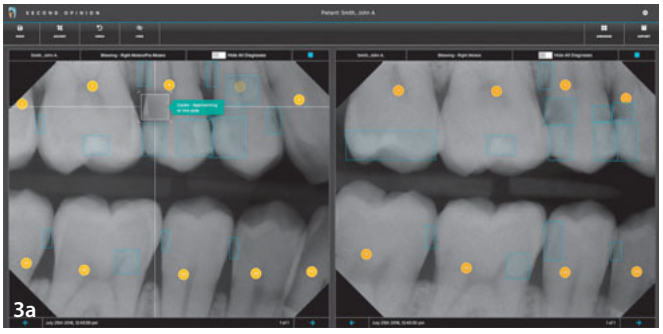
	Automated analysis	Image enhancement	Anatomy annotation	Caries detection	Treatment plan suggestion	Crown preparation margin analysis	Patient data analysis	Prosthesis design	Digital Smile Design	Orthodontics monitoring
ORCA Dental AI	•	•	•							
Denti.AI	•									
VideaHealth	•			•	•					
Pearl	•		•	•	•	•	•			
Glidewell.io								•		
Smilecloud									•	
Dental monitoring										•

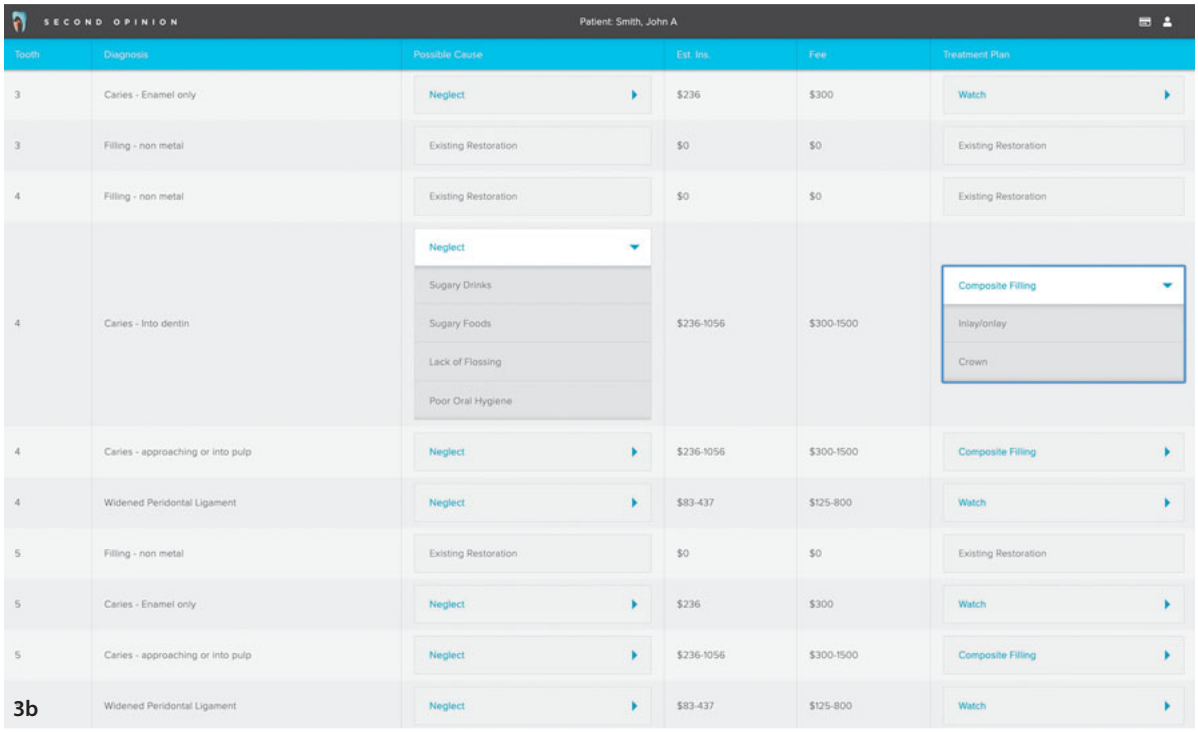
graphs was demonstrated.[11] Deep learning technology was also applied in image analysis technology. Deep learning has been utilized not only in face detection, but also in dental radiology. A pre-trained deep learning network (GoogLeNet Inception v3) can be used for diagnosis of dental caries,[12] with the accuracy of identifying dental caries in premolars, molars, and between premolars and molars at 89%, 88%, and 82%, respectively. Additional future studies will be necessary to provide a better version of the analyzing tool. However, AI-supported radiograph analysis does show a great potential of assisting clinicians to make a diagnosis as an additional reference. Commercially, start-up companies have announced their products with promising features, such as caries detection, image enhancement, and treatment plan suggestion (see Table 2). Dental radiographs can be interpreted by the software (Second Opinion, Pearl; Denti.AI; VideaDetect, VideaHealth) with machine learning algorithms (as shown in Figs 3 and 4). These software utilize computer vision to assist clinicians by automatically generating treatment proposals based on deep learning algorithms. These treatment plans can potentially be tailored to clinicians' treatment philosophies and outcomes that ultimately allow the clinician to make the final treatment decision. However, the treatment plans are still limited to simple procedures such as fillings, partial coverage, and full coverage restorations.

AI has been integrated from two-dimensional to three-dimensional (3D) applications. In 3D radiographs, such as tomography scans, the annotation of anatomical landmarks and segmentation of bone and teeth structures are achieved by AI. One company (Orca-Dental AI) introduced their software with annotation abilities, automatically segmenting anatomical structures such as the maxilla, mandible, and teeth. Nerve recognition and pathology identification are also possible with these algorithms. For analyzing purposes, generating panoramic curve in cone beam computed tomography (CBCT) scans for the clear view, exporting the segmented 3D STL files of jaws (Fig 5), and creating lateral cephalometric radiographs (Fig 6) are available in one click by accumulating expertise from big-data over time; this software has tremendous potential for self-improvement and delivery of information that is more accurate to clinicians.

Additional 3D applications have expanded outside of radiology to include intraoral scanning systems. The intraoral scans can be analyzed by dental inspection software (Smart Margin and Scan Clarity Score, Pearl). Dental clinicians can use this software to analyze their own scans to verify preparations with instant feedback. Laboratories can analyze these scans at high volume to then score the dental practitioners or categorize their preparations based on the difficulty of the case to make sure it ends up in the hands of a skilled technician. In addition, business entities such as dental service organization managers can use this technology to score their dental practitioners, to make decisions on who needs further training and who is excelling clinically. If the margin is visible and the scan is accurate, the software can then automatically mark the margins on tooth preparations with high precision (Fig 7). After margin marking, the preparation scans can move forward to digital design and milling. Additionally, an AI-based software (Glidewell.io In-Office Solution, Glidewell) is available to automate the design of single posterior crowns in the laboratory.

Smile design has been a useful tool for team communication and patient motivation. Currently, there are around 15 smile design software available for clinicians. All of these software rely on the input and preference of the clinician to design





Figs 3a and 3b Caries detection and treatment plan suggestion using AI technology. AI is used to interpret a set of bitewing images *(a)* and then structure a treatment plan *(b)* based on radiographs to aid the clinician in making treatment decisions in the software. (Image courtesy of Pearl Inc.)

Fig 4 An AI-based technology used in the detection of possible pathologic lesions. The pathologies in different x-ray modalities can be processed by well-trained AI algorithms. Suspected caries lesions (shown in red squares) in the bitewing radiograph are identified in the software. (Image courtesy of VideaHealth).

the shape and alignment of the future smile. A new interactive cloud-based platform (Smilecloud, ADN3D Biotech) incorporating digital smile design, the treatment plan, and the communication tool among clinicians, technicians, and patients was introduced. Once the required patient data (photos) are uploaded, the AI engine searches and proposes natural shapes of teeth and alignment. The proposed smile design can be versatilely modified by the clinician and then used to create an STL file for creation of a mock-up model, preparation guide, or surgical guide.

In orthodontics, decision-making could be assisted with AI. The need for orthodontic treatment conventionally is based on comprehensive exams and patient analysis. In a recent paper, a clinical decision support system was established with different clinical conditions through a Bayesian network model.[13] A different approach was introduced using artificial neural network (ANN) models for diagnosis of extraction in orthodontic patients.[14] As a result, the models had a success rate of 93% in differentiating extraction cases and non-extraction cases. How-

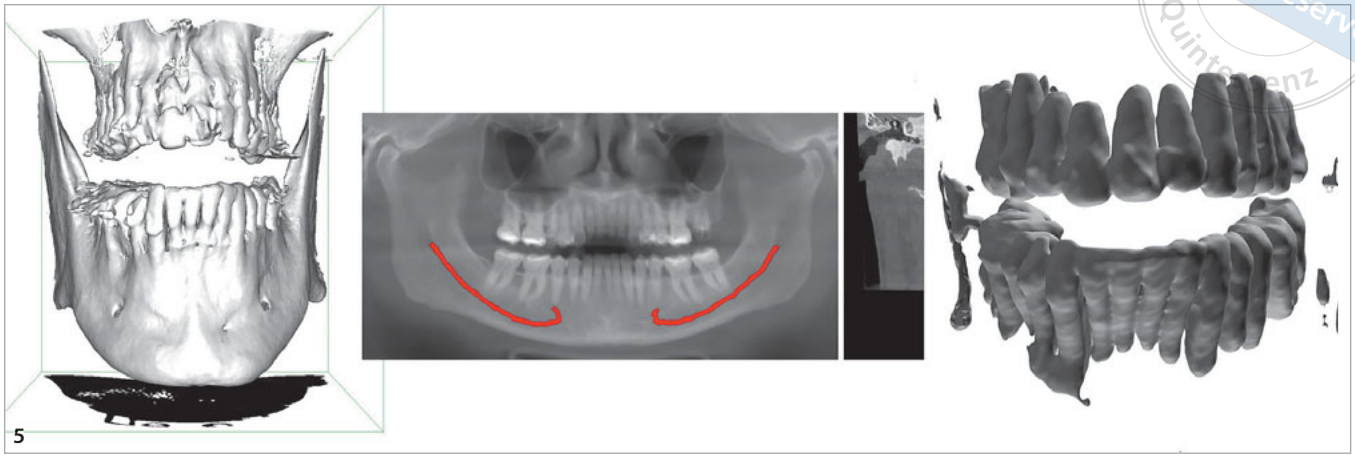


Fig 5 Automatic structure segmentation, annotation, and data conversion into STL files using AI technology. When the CBCT scan is imported to the software, the AI will instantly segment the tooth surface and bone structure, and eliminate the artifacts. The inferior alveolar nerves (red line) can be identified without human interpretation.

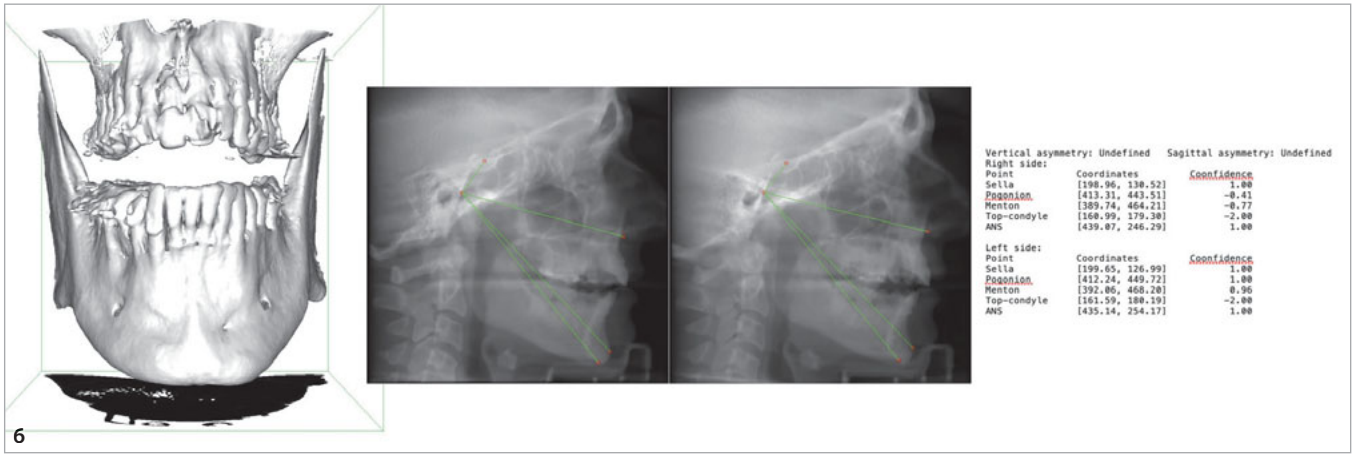


Fig 6 Automatic customized tracing and cephalometric analysis with AI technology. With the CBCT scan, the artificial intelligence can identify landmarks for cephalometric analysis. The tracing can be presented with right and left side to compare the asymmetry of the face.

ever, the model showed a decreased success rate with the detailed evaluation of the extraction patterns. It appears that the simple protocol is possible with AI in its current stage. AI can also be applied to treatment outcome analysis. In a recent paper, facial photos of pre- and post-orthodontic treatments were investigated by the pre-trained convolutional neural network (CNN) model.[15] The results revealed that AI could detect the orthodontic outcomes with an increase in facial attractiveness and a decrease in the appearance of age. In addition, machine learning was recently applied in orthodontic treatment simulation for prospective patients to pre-visualize the outcome of the treatment. An AI-based orthodontics monitoring service has also been introduced (Dental Monitoring, Dental Monitoring). The service allows patients to scan their teeth through their phones and a unique tool, and the scans can be analyzed and monitored by orthodontists to confirm the status of the orthodontic treatment.

In periodontics, methods of machine learning were adopted to explore the potential AI capabilities for understanding periodontitis differently. The CNN models were used practically to diagnose and predict periodontally compromised teeth with the radiographs.[16] Using deep learning algorithms, the diagnostic accuracy rates were 81.0% and 76.7% in premolars and molars, respectively. The accuracy of predicting extractions was

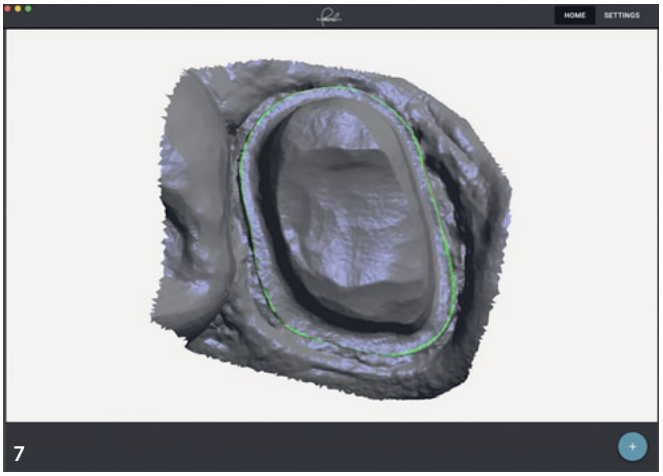


Fig 7 Margin detection using AI technology. AI is used to orient, score, and automatically mark a preparation margin before sending on for crown design in the dental laboratory.
(Image courtesy of Pearl Inc.)

82.8% and 73.4% in premolars and molars, respectively. SVM models were applied[17] for differentiation between aggressive and chronic periodontitis with the examination of the subgingival plaque to identify different microbial profiles.

Managing oral diseases has always been challenging due to the multifactorial nature of oral diseases, such as oral cancer or medication-related osteonecrosis of the jaw (MRONJ). Traditionally, it has been difficult to predict those diseases properly. It was first proposed to use AI to identify individuals with high risk factors of oral cancers using questionnaire assessment.[18] In a pilot case report, different models of machine learning were utilized to predict the occurrence of MRONJ.[19] It was concluded that using a machine learning model could achieve superior performance in prediction when compared to traditional assessments such as drug holiday or serum C-terminal telopeptide of type I collagen (CTX) level.

In research that demands the analysis of vast amounts of data, AI-aided systems are capable of analyzing the data efficiently. The decision tree model (a machine learning method) was used to investigate caries in children, correlating dental caries and periodontal health data from their parents.[20] An ANN algorithm was applied to identify the measurement of masticatory efficiency, and it was concluded that the proposed system was reliable.[21] Natural language processing has also been used in research. In a recent study, electronic health records were analyzed with natural language processing to convert chief complaints and history of temporomandibular disorders into computer language. The primary results showed that the AI-aided system had the potential to assist clinicians in differentiating temporomandibular disorders.[22] A natural language processing algorithm was also reported to be utilized to extract the smoking status of patients from electronic dental records.[23]

In forensic dentistry, the demand to identify age from the medical image is high, and the work relies on collaboration with specialists. The assistance of AI has improved forensic work, increasing efficiency. In a pilot study, an automated technique to stage mandibular third molar development was reported.[24] The age was estimated using panoramic radiographs via several machine learning methods. A similar approach was mentioned in a technical report, and a promising outcome was described. For facial reconstruction purposes, lateral cephalometric radiographs were used to predict mandibular morphology with different machine learning models.[25]

Outside of the clinical aspect of dentistry, AI is shaping new ways of assessing the practice to the field. The United States General Accounting Office reported roughly 10% of health care expenditure was wasted due to fraudulent claims.[26] In the dental insurance space, computer vision can also be used to prevent fraud, waste, and abuse, and to streamline insurance claim processes. Digital images can be analyzed by AI software (Pearl Protect, Pearl) through an insurance provider's network to create a digital fingerprint that is robust enough to recognize, even if the image is rotated, cropped, or has the contrast/brightness transformed. This allows insurance providers to notice questionable claims. In addition, radiographs are read and corroborated with the attached claim to then assign the claims into high, medium, and low confidence thresholds to better assist claims adjusters in their scrutiny of claims. High confidence claims using AI are even automatically approved to streamline the process and improve coverage for oral health care.

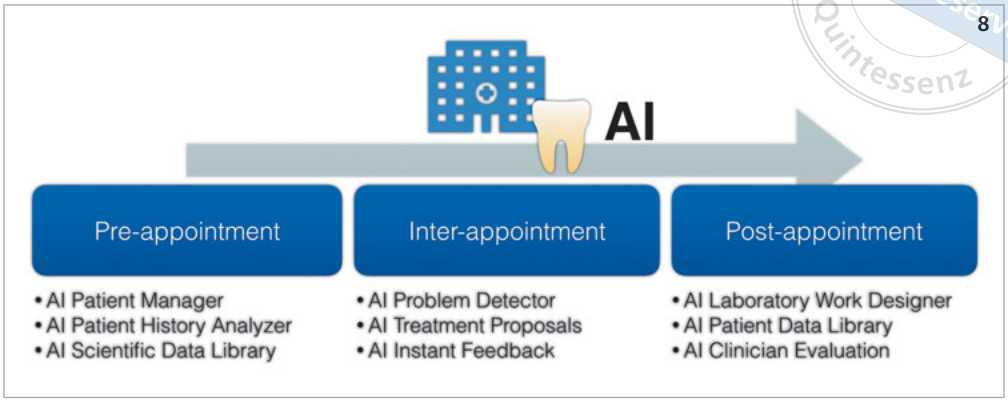


Fig 8 The future of AI Comprehensive Dental Care system. It can be categorized with pre-appointment, inter-appointment, and post-appointment AI system. These three types of AI collect the data and will be utilized for improving patient care.

Future of AI in dentistry

Due to the need for precision and instant information exchange in dentistry, AI will continue to connect with the dental profession in every aspect. The authors believe that, with the current trend and recent rapid development of AI, we can expect to see its impact on dentistry in the very near future. Machine learning, especially deep learning, will help researchers better understand certain multifactorial diseases; with its aid, it will be possible to improve the collective knowledge of oral diseases/conditions that are not currently fully understood.

In the future, we expect that dental clinics will establish an AI-Comprehensive Care System (Fig 8). Before each appointment, the AI patient history analyzer will evaluate the planned treatment with the patient's gender, age, vital signs, medical history, current medications, and health condition. The patient's dental history will be recognized from a series of radiographs and digital 3D images. With the AI patient manager, clinicians will be able to understand more about the preferences and characteristics of patients, which will improve patient management. During the appointment, the proposed diagnosis will be generated by the AI problem detector using all of the information for the clinician as a reference. Recommendations for treatment will be provided to the clinician from the AI. The critical medical concerns, such as allergies, disease interactions, and drug interactions will also be considered. Additionally, AI will provide clinicians with feedback during the treatment procedure to minimize human error. The outcome and prognosis will be predicted precisely.

Technologies designed for dental practitioners will assist clinicians in making precise diagnoses and recommendations for comprehensive treatment plans, along with calculating possibilities for each of these in a matter of seconds or less. The future "AI Dental Assistant" will be able to analyze all available information about the patient and potentially read the relevant radiographs using pre-trained algorithms. Nevertheless, this tool will not replace the clinician's role; alternatively, it will assist the dental practitioner in making an improved and highly accurate diagnosis during dental treatment. The role of AI will enable various interdisciplinary treatment proposals in treatment planning, with benefits and possible complications based on collected evidence. The knowledge in this evidence base will be updated in real time from a scientific database. However, clinicians receiving the "AI advisory" options will retain responsibility for making the right decision on their own.

With the current trend toward computer-aided design/computer-assisted manufacture (CAD/CAM), with certain materials requiring a higher level of precision in prosthodontics, a laboratory designing software incorporated with AI capability will be in high demand. This software will help lab technicians design prostheses with hygienic contours, ideal esthetics, and minimal failure expectations. For fixed dental prostheses, it will be possible to scan the existing tooth structure with an optical intraoral scanner, and then use the software to analyze and propose therapeutic options. For partial edentulism, the program will be able to utilize the algorithm to propose the possible design of removable partial dental prostheses.

Dental implant therapy will be standardized using research-based, clinically proven techniques and technology. Once a CBCT scan and intraoral scan are taken, the AI will automatically merge the two together, design the future restoration, and then place the correct implant with the proper design in the ideal position based on tissue thickness, emergence profile, bone type/thickness, and the patient's specific medical history. From there the surgical guide can be generated and the surgery can be scheduled.

Dental institutes and dental clinics will have the opportunity to build their patient library with AI in the future. With the big data including the electronic health records, digital radiographs, and the longitudinal follow-up data, it will be possible to establish a reliable source for training the AI system. Predicting prognosis will be improved with a better understanding from vast amounts of data. The AI scientific data library will keep itself updated with the current literature knowledge, as it can learn from the scientific database. In addition, hands-on testing can be completed without bias using 3D intraoral scanning for preclinical and clinical situations. Instead of each student's patient being checked by two faculty members, the patient can be scanned and the AI can give an unbiased score. This will bring trust back to grading systems and objective feedback for learning. Some dental schools such as Columbia University College of Dental Medicine are already incorporating radio frequency identification (RFID) into instruments to understand usage times, cameras into dental chairs to record procedures, and chair sensors to determine the time of patients seating and departure.[27] With all of the big data from dental schools, student doctors can learn to practice efficiently and with better ergonomics and long term results.

As AI-based services are emerging into the market, their benefits for the dental office are becoming more prominent. For general dental practitioners, AI algorithms to deliver data-driven answers are a potentially innovative way dental practices will make decisions in the future. Here, big data allows multiple ways of using AI to make business decisions in practice. For example, radiographs and intraoral scans can be used to make large-scale business decisions, such as practice acquisition, management of dental materials, and staff training. Nevertheless, it is noteworthy to mention that a basic understanding of how big data is collected and how AI algorithms are programmed is essential for dental practitioners. Knowing the advantages and current limitations of AI tools can help clinicians to select the AI service wisely as more products enter the business.

The use of AI by dental insurance will further develop and ultimately allow for immediate claim approvals. This will allow clinicians to upload their radiographs, intraoral scans, and photos to an insurance provider and instantly have an answer to their insurance claim, therefore providing transparency in the process and allowing patients to get faster dental care without the fear of no insurance coverage.

In addition to the clinical techniques, the dental patient experience will increase with the use of AI. The technology will learn patient preferences to allow for an overall better experience. AI will learn on what days and at what time the patient prefers to visit the dentist, what temperature they may like the room or chair, what music or entertainment they prefer, and even the lighting that most relaxes this patient. By improving the experience of dental patients, more patients will have proper oral health care and therefore better systemic health.

Limitations and concerns

Using AI to solve problems requires the algorithm to be comprehensive with multiple applications to solve a single question. Like the nature of data mining,[28] AI might only reflect the results subjectively with associations, not with causality. Direct interpretation will not be provided with AI; a misinterpretation might occur with the misconduct of the algorithms. AI programs still need to be developed in collaborations that involve experienced clinicians and expert computer engineers to minimize potential risks of AI. Several problems were reported[29] with IBM Watson and indicated that AI application in health care still might not be mature and requires substantial improvement.

Liability will be another growing issue if the diagnostic work begins to depend too heavily on the AI system.[30] Clinicians should always be aware and cautious when interpreting information provided by AI. Safeguarding medical information under HIPAA (Health Insurance Portability and Accountability Act of 1996) compliance in the use of AI is another concern. Most of the machine learning requires data for training. Exchange of training sets and applying models should be performed with caution to avoid violating HIPAA regulations.

Conclusion

AI technology has impacted the health care industry and led researchers and companies alike to invest in the medical field. In the authors' opinion, the progressive development of AI in dentistry will benefit clinicians and researchers to integrate different fields of knowledge and improve patient care. However, it is essential to be aware of the potential errors in interpretation of data via AI programs. To minimize output errors, it seems logical currently to combine AI technology with conventional methodologies. The authors believe that a new type of inter-professional coordination among clinicians, researchers, and engineers will be critical for the development of AI in dentistry.

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