Acta Scientific Dental Sciences (ISSN: 2581-4893)

Volume 8 Issue 5 May 2024

Review Article

AI and Dentistry: Bridging the Gap between Technology and Patient Care

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DOI: 10.31080/ASDS.2024.08.1827

Received: April 10, 2024

Published: April 18, 2024

Abstract

The fourth industrial revolution has led to the rise of Artificial Intelligence (AI) as a significant contributor to various industries, including robotics, automotive, and healthcare. AI is particularly useful in dentistry, as it can diagnose conditions that surpass human capabilities. AI research in dentistry has permeated all domains, but there is a need for a comprehensive approach to study design, data allocation, and model performance.

AI has been increasingly used in various fields, including operative dentistry, periodontics, orthodontics, and orthodontics. In operative dentistry, AI has been used to identify dental caries, vertical root fractures, apical lesions, pulp space volume, and tooth wear. In periodontics, AI has been used to diagnose periodontitis and categorize potential types of periodontal diseases. In orthodontics, AI has been used to plan and predict treatment outcomes, simulate alterations in facial photographs before and after treatment, and facilitate communication between patients and dentists.

AI is playing a significant role in Oral and Maxillofacial Pathology (OMFP), specifically in detecting tumors and cancer using radiographic, microscopic, and ultrasonographic images. In prosthodontics, AI has been used in restoration design, enhancing workflow efficiency and accuracy. AI-driven virtual dental assistants can perform tasks with enhanced precision and reduced errors and can accurately detect genetic predisposition to oral cancer.

AI has significantly transformed the field of oral surgery, forensic odontology, dentistry, and bioprinting. Robotic surgery, image-guided cranial surgery, and voice-activated dental chairs have shown efficacy in clinical settings. Bioprinting, a technology that generates living tissue and organs, has the potential to reconstruct oral tissues lost due to pathological or unintentional factors. However, the potential for AI to replace dentists remains uncertain, and its generalizability and reliability need to be assessed using external data.

Keywords: Computing Machinery; AI; Artificial Intelligence; Machine Learning

Introduction

The advent of the fourth industrial revolution has ushered in a novel digital era, wherein Artificial Intelligence (AI) emerges as a pivotal and significant contribution. As electronic devices become increasingly prevalent in people's lives, the data stored by these devices has become more extensive.

Artificial intelligence enables the seamless utilisation and analysis of data derived from electronic devices. AI is experiencing rapid growth and expansion across various industries. It can acquire knowledge from human expertise and perform tasks that require human intelligence. One of the definitions of artificial intelligence is the study and advancement of computer systems capable of executing tasks that typically necessitate human intelligence, including but not limited to visual perception, speech recognition, decision-making, and language translation [1].

Artificial intelligence (AI) has been implemented in various industrial sectors, including robotics, automotive, innovative city development, and financial analysis. Furthermore, it has found applications in medicine and dentistry, such as medical and dental imaging diagnostics, decision support systems, precision and digital medicine, drug development, wearable technology, hospital monitoring, and robotics.

AI is often considered a valuable tool for dentists and clinicians to alleviate their workload. In addition to utilising a singular information source focused on a specific disease, AI can acquire knowledge from various information sources (multi-modal data) to diagnose conditions that surpass human capabilities. For instance, fundus photographs, in conjunction with additional medical information, including age, gender, BMI, smoking habits, blood pressure, and the probability of developing diabetes, have been employed as predictive tools for heart disease [2]. Hence, the AI can identify

not only ocular conditions like diabetic retinopathy through fundus photography but also cardiovascular ailments. Image-based analysis utilising AI appears to be robust and effective. The rapid development of computing capacity (hardware), algorithmic research (software), and large databases (input data) is crucial for all of these factors. Considering these factors, there are significant opportunities to utilise AI in the dental and medical domains.

Numerous investigations are currently being conducted or have already been implemented in dentistry regarding using artificial intelligence (AI) in various domains, including diagnosis, decision-making, treatment planning, treatment outcome prediction, and disease prognosis. Numerous scholarly articles have been published on dental artificial intelligence (AI) [3-5]. This review aims to provide a comprehensive account of the evolution of AI from its early stages to the present. It will elucidate the various classifications of AI, give a concise overview of the current advancements in AI research within dentistry, and explore the interconnection between evidence-based dentistry (EBD) and AI. The present state of AI development in dentistry is also examined in terms of its limitations.

History of AI in dentistry

The origins of Artificial Intelligence (AI) can be traced back to Alan Turing's classic paper "Computing Machinery and Intelligence" published in 1950. Turing introduced the Turing Test, an assessment that ascertains whether a machine can attain intelligence comparable to a human. Nevertheless, the notion was theoretical in 1955, and limitations hindered researchers from creating tangible AI machines. The AI field experienced rapid growth from 1957 to 1974, primarily driven by advancements in computer power, increased accessibility, and better AI algorithms. One instance is ELIZA, a computer program capable of deciphering spoken language and resolving issues through textual input. The onset of AI Winters occurred during the mid-1970s and late 1980s due to inadequate practical implementations and reductions in research funding.

AI emerged in the 1980s through the use of machine learning (ML) and expert systems, two contrasting methodologies in the field. Machine learning (ML) enables computers to acquire knowledge through experiential learning, whereas expert systems emulate the decision-making capabilities of human experts. Expert systems, such as the R1 (Xcon) programme, have been extensively employed in various industries.

Significant computer vision advancements were achieved in 2012 and 2017, including the emergence of deep learning networks and the creation of renowned AI models such as Deep Blue and AlphaGo. These examples employed diverse AI methodologies to function, showcasing the capabilities of AI in multiple domains [6].

Artificial Intelligence in the field of dentistry

AI in dentistry has experienced significant growth in recent years, similar to other industries. The applications of artificial intelligence (AI) in dentistry can be categorised into four main areas: diagnosis, decision-making, treatment planning, and prediction of treatment outcomes. Diagnosis is the most widely used of all the AI applications in dentistry. AI can enhance the precision and effectiveness of diagnoses, thereby alleviating the burden on dentists. One aspect to consider is the growing dependence of dentists on computer programs for decision-making [7,8]. In contrast, computer programmes designed for dental applications progressively enhance their intelligence, precision, and dependability. AI research has permeated all domains within the field of dentistry.

Despite the publication of numerous journal articles on dental AI, it remains challenging to compare these articles in terms of study design, data allocation (such as training, test, and validation sets), and model performance (including accuracy, sensitivity, specificity, F1, AUC (Area Under the Receiver Operating Characteristic Curve), and recall). Most articles did not provide a comprehensive report on the aforementioned information. Therefore, the MI-CLAIM (Minimum Information about Clinical Artificial Intelligence Modelling) checklist has been proposed to enhance transparency and usefulness in the implementation of AI in medicine [9].

Artificial Intelligence in operative dentistry

Historically, dental professionals have employed visual and tactile or radiographic examinations to diagnose caries based on specific criteria. Nevertheless, identifying early-stage lesions poses a significant challenge in cases with deep fissures, tight interproximal contacts, and secondary lesions. Ultimately, numerous abnormalities are only identified during the later phases of dental decay, necessitating a more intricate course of treatment such as dental crowns, root canal therapy, or even dental implants. Dental radiography, including panoramic, periapical, and bitewing views and the explorer or dental probe, has been extensively utilised and recognised as highly dependable diagnostic instruments for identifying dental caries. However, most of the screening process and ultimate diagnosis depend on dentists' expertise.

Research has been conducted in operative dentistry to investigate various aspects such as identifying dental caries, vertical root fractures, apical lesions, assessing pulp space volume, and evaluating tooth wear [10]. In the context of a two-dimensional (2D) radiograph, it is essential to note that each pixel within the grayscale image possesses an intensity, or brightness, representing the object's density. By leveraging the aforementioned attributes, an artificial intelligence algorithm can acquire knowledge of the pattern and generate predictions for tooth segmentation and caries detection tasks. Lee., *et al*., [11]. created a Convolutional Neural Network (CNN) algorithm to identify dental caries on periapical radiographs. Kühnisch., *et al*., [12] proposed the CNN algorithm to detect caries on intraoral images.

Chwendicke., *et al*., [13] conducted a cost-effectiveness comparison between AI and dentists' diagnosis for proximal caries detection. The findings indicated that AI was more efficient and less expensive.

Multiple aforementioned studies have demonstrated that AI exhibits promising outcomes in the early detection of lesions, achieving accuracy levels comparable to or surpassing those of dentists. This accomplishment necessitates the collaboration of computer scientists and clinicians from different academic fields. Clinicians manually label the radiographic images to indicate the location of caries, while computer scientists prepare the dataset and machine learning algorithm. The accuracy and precision of the training results are jointly assessed and verified by clinicians and computer scientists [14].

Artificial intelligence in the field of periodontics

Periodontitis is a highly prevalent condition. It poses a significant challenge for billions of people and, if left untreated, can result in tooth mobility and potentially even tooth loss [15]. Early detection and treatment are imperative to mitigate the occurrence of severe periodontitis. In clinical practice, Periodontal disease diagnosis relies on assessing pocket probing depths and gingival recession. A commonly employed method for quantifying clinical attachment loss is the Periodontal Screening Index (PSI). Nevertheless, the clinical evaluation in question exhibits limited reliability due to its reliance on dentists' expertise, potentially resulting in the oversight of localised periodontal tissue loss [16].

AI has been employed in periodontics to diagnose periodontitis and categorise potential types of periodontal diseases. Krois., *et al*., [16] utilised Convolutional Neural Networks (CNN) to identify periodontal bone loss (PBL) on panoramic radiographs. In their study, Lee., *et al*., [11] evaluated the potential utility and precision of a proposed convolutional neural network (CNN) algorithm for the automated detection of periodontally compromised teeth.

Artificial intelligence in the field of orthodontics [17]

The formulation of orthodontic treatment plans typically relies on the expertise and personal inclinations of the orthodontists. Due to each patient's and orthodontist's individuality, the treatment is determined through a collaborative decision-making process. In the conventional approach, orthodontists encounter significant challenges in diagnosing malocclusion due to the many variables involved in cephalometric analysis. Consequently, determining an appropriate treatment plan and predicting treatment outcomes become arduous tasks. AI is a highly suitable tool for addressing orthodontic issues. AI is utilised in orthodontics to plan and predict treatment outcomes. It is employed to simulate the alterations in the visual characteristics of facial photographs before and after treatment. The use of AI algorithms greatly facilitates communication between patients and dentists by clearly visualising the impact of orthodontic treatment, skeletal patterns, and anatomic landmarks in lateral cephalograms.

Thanathornwong developed a Bayesian-based decision support system to diagnose the necessity of orthodontic treatment using orthodontics-related data as input. Xie., *et al*., introduced an artificial neural network (ANN) model to assess the necessity of extractions from lateral cephalometric radiographs. Jung., *et al*., also proposed a comparable evaluation system. In addition to its utilisation in forecasting the necessary extractions for orthodontic applications, artificial intelligence (AI) has been employed to identify cephalometric landmarks. Park., *et al*., presented a deep learning algorithm that accurately detects cephalometric landmarks on radiographs. Bulatova., *et al*., and Kunz., *et al*., created AI algorithms that achieved similar levels of accuracy as human examiners in identifying landmarks. Yu., *et al*., proposed an automated system for classifying skeletal structures based on lateral cephalometric radiographs.

In addition to identifying and categorising various cephalometric landmarks, artificial intelligence (AI) systems have been employed in orthodontic treatment planning. Choi., *et al*., introduced an artificial intelligence model that utilises lateral cephalometric radiographs to determine the necessity of surgery. The majority of orthodontic applications primarily involve the identification of landmarks and the planning of treatment, which are laborious procedures for orthodontists. An essential aspect of orthodontic treatment planning involves dividing and categorising the teeth. Artificial intelligence (AI) has been employed for various applications, including radiographs and full-arch 3D digital optical scans. Cui., *et al*., introduced multiple artificial intelligence algorithms for the automated segmentation of teeth on a digital teeth model obtained from a 3D intraoral scanner and CBCT images. In addition to the teeth segmentation, the researchers also segmented the alveolar bone, resulting in a significantly higher efficiency compared to radiologists, with a 500-fold increase in speed. The study also asserted that the algorithm demonstrates efficacy in complex scenarios involving diverse dental abnormalities.

Artificial intelligence in the field of oral and maxillofacial pathology

Artificial Intelligence (AI) plays a crucial role in Oral and Maxillofacial Pathology (OMFP), which focuses on examining and diagnosing pathological conditions affecting the oral and maxillofacial region. Oral cancer is the most severe form of OMFP, with an annual global incidence exceeding 657,000 cases and a mortality rate of over 330,000 individuals. AI research has focused on detecting tumours and cancer using radiographic, microscopic, and ultrasonographic images.

AI can identify abnormal locations on radiographs, including nerves within the oral cavity, interdigitated tongue muscles, parotid, and salivary glands. CNN algorithms have demonstrated efficacy in automated cancer detection and contribute to the management of cleft lip and palate in various aspects, such as risk prediction, diagnosis, pre-surgical orthopaedics, speech assessment, and surgery.

Timely identification and assessment of diverse mucosal lesions are crucial for categorising them as benign or malignant. Pathologists use microscopic techniques to diagnose diseases by examining the morphology of stained specimens on glass slides. AI can serve as an appropriate tool to assist pathologists in this undertaking.

Several studies have employed convolutional neural networks (CNN) to identify oral potentially malignant disorders (OPMDs) and oral squamous cell carcinoma (OSCC) within intraoral optical images. AlexNet, a CNN algorithm, was used to differentiate between normal and abnormal head and neck mucosa. Abureville., *et al*. autonomously detected oral squamous cell carcinoma (SCC) based on confocal laser endomicroscopy images, with an accuracy rate of 83% and a diagnostic time of 38 seconds [17].

Artificial intelligence in the field of prosthodontics

The use of AI in prosthodontics, specifically in restoration design, has increased. The implementation of CAD/CAM technology has facilitated the digitisation of the design process in commercial products such as CEREC, Sirona, and 3Shape. However, it remains incapable of attaining personalised designs tailored to individual patients. Hwang., *et al*. and Tian., *et al*. introduced innovative methods utilising 2D-GAN models to produce crowns by acquiring knowledge from technicians' designs. Ding introduced a 3DDCGAN network for crown generation, which utilised 3D data directly during the process, yielding crowns that closely resemble natural teeth in terms of morphology. Combining artificial intelligence with CAD/CAM or 3D/4D printing can enhance workflow efficiency and accuracy of shade matching and debonding prediction. Nevertheless, creating removable prosthodontics is more complex as it involves many factors and variables. Currently, no machine learning algorithm is directly applicable to the design of removable dentures. However, several expert systems have been developed and implemented. Machine learning algorithms primarily focus on aiding the design procedure of removable dentures, specifically in tasks such as categorising dental arches and predicting facial appearance in patients without teeth.

Other dental applications of AI

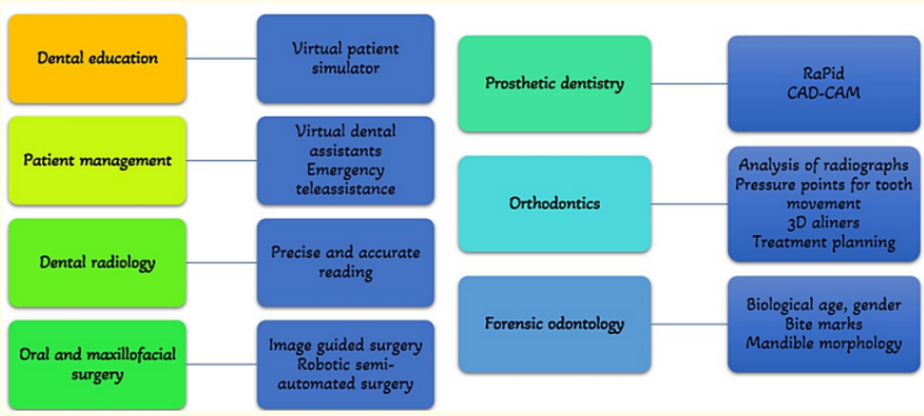

Figure a

In the field of dental education

Intelligent tutoring systems have made substantial progress since their inception in the 1980s. AI is commonly used in dental education to create realistic scenarios that simulate clinical work on patients and reduce the risks associated with training on a live patient. Consequently, there has been a notable enhancement in providing preclinical virtual patient feedback to the students. The interactive interphase fosters high-quality learning environments, enabling students to evaluate and compare their work to the ideal. Multiple studies have demonstrated that students acquire a competency-based skill level more rapidly when using these systems than traditional simulator units [18].

In the context of patient management

Artificial intelligence-driven virtual dental assistants can perform various tasks within dental offices with enhanced precision and reduced errors while necessitating less human labour than their human counterparts. It facilitates clinical diagnosis, treatment planning, visit scheduling, insurance organisation, paperwork management, and other tasks. Providing the dentist with information about the patient's medical history and habits, such as smoking and drinking, is hugely beneficial. In situations involving dental emergencies, mainly when the practitioner is unavailable, patients are provided with the alternative of emergency teleassistance [19].

In the context of diagnosis, treatment, and prognosis

Artificial intelligence can be advantageous in diagnosing and treating oral cavity diseases and detecting and classifying suspiciously altered mucosa that exhibits premalignant and malignant changes. Even minute alterations at the pixel level that may go unnoticed by the human eye are detected. Artificial intelligence has the potential to accurately detect the genetic predisposition of a large population to oral cancer [19]. An AI-based machine learning system is a valuable tool for assessing dental prognosis concerning the treatment strategy. To evaluate a tooth's long-term oral health and function, it is imperative to conduct a comprehensive evaluation of the treatment strategy [20].

In the field of dental radiology

AI is increasingly being integrated into radiology in dentistry, particularly diagnostic procedures such as digital RVGS/IOPA, 3D scans, and CBCT. Substantial data needs to be collected and analysed to develop an artificial intelligence system that can assist in rapid diagnosis and treatment planning [21].

In the field of oral and maxillofacial surgery

The most significant application of artificial intelligence in oral surgery is the advancement of robotic surgery, which involves the replication of human body motion and intellect. Image-guided cranial surgery procedures, such as dental implant placement, tumour and foreign object removal, biopsies, and temporomandibular joint (TMJ) surgery, have demonstrated efficacy in clinical settings. Studies comparing oral implant surgery show a notable enhancement in accuracy compared to the freehand procedure, even when carried out by skilled surgeons. Furthermore, a lack of noticeable distinction was observed between surgeons with extensive experience and those undergoing training. Typically, there have been reports of reduced operation duration, improved intraoperative precision, and safer handling of fragile structures. Image guidance has the potential to enhance the comprehensiveness of surgical resection, thereby potentially mitigating the necessity for subsequent surgeries [19]. The field of surgery has experienced a significant transformation due to the advancements in artificial intelligence (AI). Currently, there are multiple robotic surgeons who, with increasing effectiveness, perform partially automated surgical procedures while being supervised by a proficient surgeon [18].

In the field of forensic odontology

In forensic odontology, artificial intelligence (AI) has emerged as a significant scientific advancement that has found widespread application. The method has demonstrated substantial efficacy in ascertaining the biological age and gender of healthy and ill individuals. Furthermore, it examines bite marks and anticipates mandibular morphology [15].

Artificial intelligence (AI) is poised to yield significant advantages for dentistry. The Dental Chair, an essential element of dental practice, underwent a substantial transformation from a physiologic, hydraulic pressure chair equipped with a manual pump to an electric chair equipped with multiple sensors. The latest advancement is a voice-activated dental chair that eliminates the need for physical intervention by the doctor. All operations are performed using voice commands. In the near future, dental chairs will be able to monitor a patient's vital signs, anxiety level, weight, and duration of the procedure while simultaneously providing comfort to the patient and alerting the operating doctors in the event of any deviations, among other functions. This is due to the relentless efforts of all brilliant individuals in AI [21].

Lastly, an innovative application of artificial intelligence (AI) can be observed in "bioprinting." This technology enables the generation of living tissue and organs through the sequential deposition of thin layers of cells. It holds the potential for the reconstruction of oral hard and soft tissues lost due to pathological or unintentional factors [18].

The influence of artificial intelligence on dental professionals

Despite the extensive debate surrounding the potential impact of AI on dentistry, uncertainties persist regarding its ability to supplant dentists entirely. Automated dentistry, devoid of human intervention, does not accurately reflect clinical care. The absence of clinical intuition, intangible perception, and empathy in machines hinders their ability to deliver personalised healthcare and maintain professionalism. Translating human-to-human communication into computer language poses a significant challenge, as highlighted by previous research [22].

Limitations and Future Outlook

Notwithstanding the AI models' encouraging outcomes, it remains imperative to ascertain their generalizability and reliability by utilising suitable external data acquired from recently registered patients or gathered from alternative dental establishments. The future objectives of AI research in dentistry encompass expanding the capabilities of AI models to achieve expert-level performance and identifying early lesions that are imperceptible to the human eye [23].

The use of artificial intelligence (AI) in dentistry has the potential to enhance the quality of dental care delivered by professionals to their patients. Dentists can potentially utilise artificial intelligence (AI) systems as an adjunctive instrument to improve the accuracy of diagnosis, treatment planning, and treatment outcome prediction. General dentists can benefit from the diagnostic assistance offered by deep-learning technologies. The utilisation of automated technology has the potential to enhance clinical processes and increase physician productivity. For instance, one example of this is the computerised completion of electronic dental records through the identification and numbering of teeth. The utilisation of these systems for secondary views has the potential to enhance the precision of the diagnosis [24].

Summary

The application of artificial intelligence technology in endodontics has been extensive. Research on the application of AI in endodontics has shown that neural networks exhibit comparable performance to dental experts, demonstrating higher accuracy and precision. In certain studies, artificial intelligence models have shown superior performance to specialists. Based on the findings of the studies, it is suggested that these applications may offer more excellent utility to individuals who are new to the field or lack advanced expertise.

Conclusion

AI should be seen as an augmentation tool that helps dentists perform more valuable tasks, such as integrating patient information and enhancing professional relationships, by comple-

menting and occasionally relieving them. Contemporary artificial intelligence demonstrates exceptional proficiency in leveraging structured knowledge and extracting insights from extensive datasets. However, it cannot form connections like the human brain and has a limited capacity to make intricate decisions in a clinical setting. In situations with ambiguity, dentists' expertise is required to perform physical examinations, gather medical histories, assess cosmetic outcomes, and facilitate conversation. It is imperative to emphasise that effective communication between patients and dentists necessitates the utilisation of nonverbal cues to determine the patient's aspirations, concerns, and anticipations. Despite the ongoing debates surrounding the incorporation of empathy into algorithms designed for affective robots to express artificial emotions, this assertion remains valid. The communication pathways in question exhibit an intuitive and spontaneous nature.

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