Integrating artificial intelligence (AI) in modern dental practice – Practical, Ethical, and Legal considerations

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Executive summary

Rationale / Importance

- Artificial Intelligence (AI) holds immense advantage in dental practice, offering innovative solutions to enhance patient care, improve treatment outcomes, and streamline practice management.
- This review explores the role of AI and its current applications and benefits, emerging trends, and the practical, ethical and legal challenges of integrating AI in the dental practice setting, shedding light on both its promise and complexity.

Key points

- Key areas where AI is expected to make significant contributions include diagnostic imaging analysis, treatment planning assistance, patient communication and management, and practice management optimization.
- By embracing AI, dental professionals can deliver higher-quality care, optimize patient outcomes, and streamline practice workflow and management efficiency.
- While the integration of AI is reshaping every aspect of dental practice, it is important to note that human expertise and clinical judgement remain essential elements of everyday clinical practice.

Practice implications

- Integrating AI into dental practice requires careful consideration of logistical, ethical, and legal challenges to facilitate seamless integration into daily workflows without disrupting patient care, and staff training requirements.
- Successful implementation will depend on addressing these challenges and ensuring that the technology is used to complement, rather than replace, the expertise and judgment of dental professionals.
- The biggest hurdle for AI lies not in determining its capabilities but rather in ensuring its acceptance in routine clinical practice.
- With proper training and education, challenges and obstacles can be overcome, paving the way for a more advanced and efficient dental care system.

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Background

In recent years, the intersection of AI-technologies and healthcare has ushered in a new era of innovation, a transformative force revolutionizing and reshaping the way we approach how medical and dental services are delivered, diagnostics are made, and treatments are administered.[1-4] The application of AI in dentistry has seen an explosive growth over the past decade [5,6] and has tremendous potential to positively disrupt and transform the current practice of dentistry.[7]

Owing to the rapid development of three cornerstones of AI technology, namely big data coming through digital devices, computational power, and sophistication of AI algorithms in the past two decades, AI applications are rapidly developing to provide convenience to dentists lives in the dental practice setting[5] by enhancing diagnostic accuracy, facilitating personalized treatment planning, optimising practice workflow and efficacy, and enhancing patient experiences and treatment outcomes.[3,8-10]

Embracing AI however, comes with several challenges and complexities.[11] Furthermore, currently, there are no well-defined regulations in place to address the legal and ethical issues that may arise due to the use of artificial intelligence in healthcare settings.[12] For dentists, it remains crucial to understand and address these complexities and challenges, ultimately fostering innovation in modern dental practice, while upholding the highest ethical standards and promoting patient welfare.

AI encompasses a broad spectrum of emerging technologies that continue to influence every aspect of daily life.[11,13,14] It refers to the development of computer systems or machines that can perform tasks such as visual image perception, speech recognition, decision-making, and language translation, that typically require human intelligence to complete.[2,5,15] To perform tasks that simulate intelligent human cognitive functions, AI technologies utilize machine and deep learning techniques, computer algorithms, cognitive computing, computer vision, and natural language processing.[5,15]

Augmented intelligence (AugI), involves using AI as a supplementary tool to assist or enhance human intelligence, rather than replacing it, to improve decision-making, problem-solving, and overall performance of various tasks.[11,15-17] AugI aims to complement human capabilities by leveraging AI algorithms to analyse vast amounts of data, to generate actionable insights, and assist in making more informed decisions, ultimately amplifying human potential and productivity.

Purpose and Methodology

The purpose of this narrative review is to provide an overview of current applications of AI in dentistry, emerging trends and future directions, and the practical, ethical, and legal considerations that dentists have to anticipate when integrating AI-technologies into their practices. This knowledge is aimed at helping dental professionals understand the challenges of using AI as a supplementary tool to assist in their routine work with improved efficiency, whilst highlighting its potential to enhance diagnostic accuracy, personalize treatment planning, streamline workflow, and foster continuous learning and improvement in dental practice.

ChatGPT, an AI language model developed by OpenAI, was used to glean information for structuring and organizing this review into coherent sections, and to contextualize various aspects of AI's impact on dentistry from current applications to future prospects, practical challenges, ethical and legal considerations within the dental practice ecosystem. All ChatGPT derived information was verified for accuracy of content and context by systematically searching and referencing scientific open access databases [i.e., MEDLINE/PubMed Central, Google Scholar, Directory of Open Access Journals (DOAJ), arXiv, PLOS and CORE (COnnecting REpositories)] for appropriate evidence-based and/or supporting literature.

Current applications of AI in dental practice

AI has entered various fields of dentistry, including dental radiology and oral maxillofacial radiology[18,19,] restorative and aesthetic dentistry[20], periodontology [21-24,] endodontics[25-30], orthodontics[31-33], implantology[34-40], oral and maxillofacial surgery[41-46,] and practice management.[11,14,17,47,48] Detailed examples of how AI is used in clinical dental practice are described in several recent reviews.[3-5,11,16, 33,44,47,49-55]

The current applications of AI in dentistry can be classified into the following groups:

Image analysis and diagnostic tool

AI has made significant advancements in the field of diagnosis in dentistry, revolutionizing the way anatomy and oral diseases are detected and diagnosed. AI-powered dental imaging software (i.e., Diagnocat™, Pearl™, Denti. AI™) can analyse dental radiographs, CBCT scans, and intra-oral images, in real time to assist dentists in identifying pathologies or detect abnormalities such as dental caries, vertical root fractures, apical lesions, periodontal diseases, salivary gland disease, maxillary sinusitis, alveolar bone loss, and oral tumors in X-rays with more accurately and earlier

than traditional methods.[7,19,42,55-60]

AI models are also in used oral and maxillofacial radiology to provide quantitative and qualitative radiographic assessment, i.e., cephalometric analysis, segmenting anatomic structures, image enhancement and manipulation.[7,61,62] AI can also be used for classifying, detecting, or segmenting oral mucosal lesions on photographs.[63]

One of the primary benefits of AI in dentistry is its ability to improve diagnostic accuracy and early detection of oral diseases. By detecting pathologies at an early stage, dentists can intervene promptly and implement appropriate treatment strategies, leading to better patient care outcomes.[5,16,53,56,60,64,65]

Clinical decision support and personalized treatment planning

AI facilitates personalized treatment planning by synthesizing patient data, clinical guidelines, and evidence-based practices to tailor interventions to individual patient needs. By analysing patient data, AI algorithms can recommend optimal treatment options, predict treatment outcomes, and anticipate potential complications.[8,56,60] AI-driven clinical decision support tools can assist dentists in interpreting diagnostic images, reviewing treatment plans, and documenting patient encounters, saving time and improving productivity.[8] This leads to improved efficiency, reduced wait times, enhanced patient satisfaction, and adherence to treatment regimens.

Examples of AI-driven clinical decision support and treatment planning applications in the dental field include the following:

Orthodontics: AI models can assist in treatment planning for procedures such as predicting need for orthodontic treatments,[20,32] orthodontic extractions and orthognathic surgery[44,48,] automated landmark detection in lateral cephalograms (i.e. WebCeph™, CephX™, AudaxCeph™, IPS Case Planner™), age and gender determination, skeletal growth and maturation assessment, airway volume assessment[48,67,] and diagnostic orthodontic work-up, virtual monitoring (Invisalign® Virtual Care AI).[66] In some studies it was found that these systems were even able to outmatch dental specialists in terms of performance and accuracy.[33,56,66,68]

Dental Implantology: AI can assist in treatment planning for guided implant placement surgery [i.e., IconiX™, 3SHAPE™ Implant Studio, CoDiagnostiX10™ (Straumann)] [34-36,38-40] It is suggested that AI-driven software can recommend optimal treatment options, predict treatment outcomes, and anticipate potential complications, allowing for more effective and customized treatment approaches, leading to better outcomes. (i.e., OraQ™)[8,56,68] AI models for implant type recognition, implant success prediction, and implant design optimization have demonstrated great potential but are still in development.[34,37]

Periodontology: Touchless voice charting AI is used for periodontal charting to determine diagnosis, risk, prognosis as well as treatment choices and clinical notes. (i.e. Bola AI™, Denti.AI™)[21-24,65,69]

Oral Maxillofacial Surgery: AI is used to assist diagnosing and planning treatment with the least possible error such as predicting internal derangements in cases with TMJ disorders[41-43,] the detection of impacted third molar teeth and their relationship to anatomical structures[70,] and orthognathic surgery[46,70,] and virtual guided surgical treatment planning.[45]

Endodontics: AI is used as a diagnostic tool to assess treatment outcomes, detection of apical lesion, root fractures or assessing the quality of existing root canal fillings.[26] Pre-treatment planning including work length determination, root canal system morphology, and prediction of endodontic retreatment outcome (i.e.Diagnocat™). In endodontics, in terms of disease detection, evaluation, and prediction, AI has demonstrated accuracy and precision.[25,26,28,30] AI can aid in the advancement of endodontic diagnosis and therapy, thus enhancing endodontic treatment results.

Prosthodontic: Dental prosthetic use has been a leader in the use of AI with chairside dental design, digital wax-ups and milling CAD/CAM systems.[71] AI holds promise in assisting dentists and technicians with digital restorative design in obtaining morphology templates that closely resemble the original shape of the defective teeth. These customized templates serve as a foundation for enhancing the efficiency and precision of digital restorative and prosthesis design.[36,71-73]

Aesthetic dentistry

AI can assist in treatment planning for procedures such as aesthetic dentistry or digital smile design (i.e., DSD™ and Smilefy™) Digital smile design software software also allows the clinician to educate the patients regarding the improvements that can be done and also helps in collecting

the patient's own preferences and requirements, thereby making the patient feel like he is a part of the decision-making process rather than just being on the receiving end.[74] The DSD workflow begins with digital scanning of the patient's dentition using an intraoral scanner, which is then imported to the respective DSD software. Using the various different shapes and forms available in the digital repository, the dentist can overlap the teeth for a given aesthetic procedure.[74]

Patient risk and treatment risk prediction

AI algorithms can analyse patient data to identify or predict patient-specific risks, such as likelihood of developing dental caries, periodontal disease, oral cancer or endodontic or implant failure.[75-77] By identifying high-risk patients early on, dentists can implement targeted preventive measures and personalized treatment plans to maintain oral health and prevent disease progression and future complications.[8]

Optimize clinical workflow efficiency

The DEXIS™ digital ecosystem [78] is an interconnected, AI-powered platform for digital implant workflow—combining cutting-edge CBCT, intraoral scanning, diagnostics, and treatment planning to optimise clinical workflow efficiency.8. AI-powered eco-systems empowers clinicians to manage each step of the implant case, from diagnosis to delivery, with one, integrated toolset, while preserving complete flexibility to adapt their workflows based on the individual needs of each case.[8] Invisalign® has an AI-powered platform for digital clear aligner workflow, including diagnostic orthodontic work-up and virtual monitoring (Invisalign® Virtual Care AI).[66] and orthodontic treatment outcome simulation (i.e., Invisalign® Outcome Simulator Pro)[66,79]

Opitimise practice management and operational efficiency

AI driven cloud-based technologies (i.e., Adit)[80] and AI-powered chatbots optimize operational efficiency by automating administrative tasks such as appointment scheduling, reminders, and follow-ups, freeing up staff time and administrative burdens. [8] AI-driven scheduling systems minimize wait times, maximize operatory utilization, and enhance the overall patient experience.

Enhanced Patient Communication and Education:

Effective patient education and communication are integral components of quality dental care, contributing to informed decision-making, treatment compliance, and positive clinical outcomes.[81] AI-powered chatbots and virtual assistants improve patient communication by providing instant responses to inquiries, and delivering educational content.[8,81] This enhances patient engagement, satisfaction, and adherence to treatment regimens ultimately leading to better oral health outcomes and improved patient experience.

Augmented reality (AR) or virtual reality (VR) systems (i.e., OraQ AI) can overlay digital information onto the dentist's field of view, offering visual guidance and image overlays during procedures such as digital smile design, dental implant placement, orthodontic treatment planning, and orthognathic surgery.

Limitations of current AI applications

AI is increasing the scope of state-of-the-art models in dentistry but is still under development. Further studies are required to assess the clinical performance of AI techniques in dentistry.[4] Clinical decision support systems incorporate knowledge with patient-specific data to serve clinicians with supportive tools that enhance their clinical decision-making process.[32] However, a limitation of these AI algorithms is that they have not been validated and require caution by clinicians in terms of utilizing the provided predictions as well as monitoring treatments' results.[26,82] Moreover, these technological advancements also require the integration of multi-source data capture, including clinical information and three-dimensional imaging such as CBCT, digital dental models (DDMs), photographs, lateral cephalogram and panoramic x-rays.[84] It is also suggested, before incorporating AI models into routine clinical operations, it is still important to further certify the cost-effectiveness, dependability, and applicability of these models.[85]

Emerging trends and future directions in AI technology

Emerging trends in AI-driven technologies are reshaping the landscape of dental practice, empowering dentists with innovative tools and solutions to deliver higher-quality care, improve patient outcomes, and adapt to the evolving demands of the digital age.[11] The most eminent emerging trends and future directions in AI-driven technologies specifically in dental practice include:

Advanced Diagnostic Imaging

Future advancements may include the development of AI algorithms for early detection of oral cancers and microscopic abnormalities86, quantitative assessment of periodontal disease progression, and automated analysis of 3D imaging data for implant planning and placement.[2] This will enable earlier intervention and improved patient

outcomes. AI's role in dentistry is poised to enhance diagnostic and treatment capabilities while optimizing CBCT scans, ultimately improving patient care.[87] Future aims of AI research in the dentistry sector include not only raising the performance of AI models to expert levels but also detecting early lesions that are invisible to the human eye.[2,87]

Personalized treatment planning

AI-driven approaches will enable dentists to develop more personalized and precise treatment plans tailored to individual patient needs and preferences. Future directions may include the integration of genomic and biomarker data, microbiomic, immunological and lifestyle factors into AI algorithms for predicting treatment response, optimizing treatment outcomes, and reducing the risk of adverse events or complications.[2]

Conversational agents, Tele-Dentistry and Remote Monitoring

Tele-dentistry, facilitated by AI technologies, has emerged as a valuable tool for remote consultations and monitoring.[89] Patients can receive advice and follow-up care without the need for physical visits to the dental office.[90]

Conversational agents (CAs) are AI programs that engage in a dialogue with users by interpreting their questions or concerns and replying to them in a text message, image, or voice format.[89,91] CA's typically imitate human conversation by applying natural language processing and machine learning and stand in contrast to text-based engagement platforms that accept discretely formatted human inputs and reply with preset messages.[91]

Future developments may include AI-powered tele-dentistry platforms for real-time analysis of intraoral images, remote patient education and coaching, and integration with wearable devices for continuous remote monitoring of oral health parameters.

AI-driven tele-dentistry platforms and remote monitoring solutions will enable dentists to remotely assess patient oral health, provide virtual consultations, and monitor treatment progress.[2,89] These technologies will improve access to dental care, particularly in underserved areas, and enhance patient engagement and compliance with treatment plans.[2,89]

Virtual Treatment Planning and Simulation

Augmented Reality (AR) overlays digital information onto the real-world environment, enhancing perception and interaction with physical objects. In dental practice, AR can be used for patient education and treatment planning by overlaying digital models of teeth, gums, and dental prosthetics onto the patient's oral cavity in real-time.[2,81] AI-driven software will enable virtual treatment planning and simulation for dental procedures, including orthodontic treatment, implant placement, and restorative dentistry. Dentists and patients can use AR headsets or mobile devices to visualize treatment outcomes, simulate dental procedures, and communicate treatment plans with patients more effectively, leading to improved treatment outcomes and patient satisfaction.[81]

Interactive patient engagement and education

Virtual assistants and Chatbots powered by AI are streamlining patient communication, making informed decisionmaking more convenient, and providing patients with information about oral hygiene practices and dental procedures.[90] Chatbots such as ChatGPT facilitates virtual consultations, educates patients, and serve as a real-time surgical assistant during procedures.[92] These tools can provide patients with immediate answers to their queries, help with pre-visit preparations, and offer post-treatment care advice, enhancing patient engagement and satisfaction.

AI driven software will provide interactive educational tools and applications for patients, using animations, simulations, and virtual models to explain and help patients better understand their oral health condition, treatment options, and preventive measures more effectively.81 Augmented reality (AR) and virtual reality (VR) technology can assist dentists in explaining various dental procedures to their patients, using interactive methods.[81] With 3D models showing patients' teeth, gums, and oral cavities, dentists can make out a diagnosis, set a treatment plan, and visually present expected results in an understandable way. Patients can also study several treatment options to make an informed decision about their oral health.[81] This will improve patient engagement, compliance, and overall satisfaction with dental care.

Virtual Training and Simulation:

AI-powered simulation tools can provide dental professionals with realistic practice scenarios, improving their skills and reducing the risk of errors during actual procedures. Virtual (VR) and Augmented (AR) Reality creates immersive, computer-generated environments that users can interact with and explore using specialized headsets or devices. In dentistry, a VR training simulator can be used for dental education and training, allowing students and dentists to practice simulated

dental procedures in a realistic virtual environment without the need for physical models or patients. This method can be especially useful for complex procedures requiring careful planning and high precision, like oral surgery or implant installation. VR-based simulations can help develop clinical skills, improve hand-eye coordination, and gain confidence in performing complex dental procedures in a risk-free, controlled setting. One of the main advantages of using VR and AR for training is the ability to practice anywhere, even at home. Besides, you can conduct joint training with people who are in different places. It helps to share experiences and set up the most effective communication between specialists.

Overall, AR, VR, and MR technologies and ChatGPT applications can offer innovative solutions for dental education, training, treatment planning, and patient communication.[1, 2,93,94,95,96] By leveraging these immersive technologies, dental professionals can enhance clinical outcomes, improve patient experiences, and advance the practice of dentistry in the digital age. AI can help tailor continuing education programs to the specific needs of dental professionals, ensuring they stay updated with the latest advancements and techniques.

Predictive Analytics and Preventive Care

AI will play a critical role in advancing predictive analytics and preventive care initiatives in dentistry by identifying at-risk patients, predicting disease progression, and recommending targeted interventions to maintain oral health. Future directions may include the development of AI-driven risk assessment tools for early identification of individuals at high risk of developing oral diseases, implant prognosis, personalized preventive care plans, and remote monitoring strategies for proactive disease management, and reduce the need for invasive treatments. [97]

Practice Management Solutions:

Virtual assistants powered by AI are streamlining administrative tasks, making appointment scheduling, sending reminders, and follow-ups automated and more convenient and efficient, reducing no-show rates and improving patient adherence to treatment plans.[90] Chatbots such as ChatGPT facilitates virtual consultations, educates patients, and serves as a real-time surgical assistant during procedures.[92]

AI-powered practice management solutions automate administrative tasks, such as billing, insurance claims processing, and inventory management, allowing dental staff to focus more on patient care, optimize scheduling, and improve workflow efficiency in dental practices, reducing the administrative burden on dental practices, and allow dentists to focus more on patient care.[2] Practices will be able to utilize AI to forecast trends in patient flow, optimize resource allocation, and manage workforce scheduling more effectively.

Robotics-assisted and guided surgery

The future application of AI-driven robotics in guided surgery holds immense promise for revolutionizing dental practice. By combining artificial intelligence with robotic technology, guided surgery systems can enhance precision, accuracy, and efficiency in dental procedures such as implant placement and oral surgeries, reduce the risk of complications, improving patient outcomes and reduce the physical demand of dental work.[2,11,45,90,98,99]

AI algorithms analyze patient data, diagnostic images, and treatment plans to generate precise surgical paths and optimize implant positioning in real-time. Robotic systems execute these plans with submillimeter accuracy, reducing the risk of complications and improving treatment outcomes. Additionally, AI-driven robotics enable real-time feedback and adaptive control during surgery, allowing for adjustments to be made based on intraoperative conditions. This convergence of AI and robotics in guided surgery heralds a new era of precision dentistry, where advanced technologies work synergistically to deliver optimal results and improve patient care.[98] The future of implant dentistry lies in harnessing the potential of robotics and AI while upholding the highest standards of patient care and ethical practice.[11]

Research, innovation and development

AI also plays a crucial role in the research and development of dental treatments. By facilitating the analysis of vast datasets, AI contributes to the discovery of new materials and drugs for restorative dentistry.[90] AI systems have the capability to continuously learn and improve over time by analysing feedback from users, refining algorithms, and adapting to changing clinical contexts. By leveraging techniques such as reinforcement learning and deep learning, AI algorithms can evolve to become increasingly accurate, reliable, and clinically relevant. AI will accelerate research in dentistry by analysing large datasets of patient records, clinical trials, and scientific literature.[2] AI-driven approaches will also facilitate drug discovery for oral diseases, advancements in materials science for dental prosthetics and implants, and the development of predictive models for treatment outcomes and disease progression. AI-driven research in dentistry holds the promise of accelerating advancements in diagnostic

techniques, treatment modalities, and preventive strategies. By analysing large datasets and identifying patterns in patient outcomes, AI contributes to evidence-based practice and drives innovation in dental care, ultimately leading to better outcomes for patients and practitioners alike.[2]

Challenges and obstacles with adopting AI-technologies in dentistry practice

Although AI-driven technologies offer numerous benefits for transforming dentistry and improving patient care, dentists may face several challenges and obstacles in adopting AI technologies and applications to realize its full potential.[2] While the integration of AI in dental practice holds promise for improving diagnostics, treatment planning, and patient outcomes, it also requires careful consideration of practical, logistical, ethical, and legal challenges to ensure that AI technologies are deployed responsibly and ethically.[65]

Dentists and AI developers must navigate these logistical, ethical, and legal challenges thoughtfully, ensuring that AI technologies are deployed responsibly, ethically, and in accordance with applicable laws and regulations, while prioritizing patient safety, autonomy, and well-being. Collaboration between stakeholders, including dental professionals, AI developers, regulators, policymakers, and ethicists, is essential to address these issues and foster a culture of ethical and responsible innovation in dentistry that will ultimately maximise the potential benefits of AI in dentistry while mitigating potential risks.

Logistical Challenges

Integrating AI into dental practice faces logistical hurdles such as costs associated with purchasing and maintaining AI-enabled equipment and software, compatibility with existing digital systems, integration with electronic health records, and training requirements. Ensuring seamless integration into daily workflows without disrupting patient care is crucial. Additionally, maintaining and updating AI systems to keep pace with evolving technology adds another layer of logistical complexity.

Dentists and dental staff may require extensive training and education to effectively utilize AI technologies. Additionally, there may be concerns about the accuracy and reliability of AI algorithms, as well as the need for robust validation and testing procedures to ensure optimal performance.

Adoption and Acceptance

Despite the potential benefits of AI in dentistry, widespread adoption and acceptance by dental professionals may be hindered by factors such as cost, accessibility, and resistance to change and the learning curve. Dentists may be hesitant to adopt AI technologies due to concerns about reliability, usability, and perceived threats to professional autonomy. The biggest hurdle for AI lies not in determining its capabilities but rather in ensuring its acceptance in routine clinical practice.[22] Overcoming barriers to adoption will require effective education, training, and demonstration of the value proposition of AI in improving clinical outcomes and practice efficiency.[98]

Cost

Implementing AI systems often requires significant initial set-up investment associated with purchasing and maintaining AI-enabled equipment and software, training, and integration with existing systems, which may be prohibitive for smaller dental practices.[100]

Compatibility and integration with existing systems

Dental practices often use a variety of digital systems and software solutions for managing patient electronic health records, imaging data, and treatment plans. Ensuring seamless interoperability and integration between these systems to enable data exchange and workflow automation presents a significant challenge. Without standardized data formats and interoperability standards, integrating AI technologies into existing dental workflows may be cumbersome and inefficient.[68,100] Integrating AI technologies with existing dental practice management systems and workflows can be complex and time-consuming, requiring careful planning and customization.

Data quality and quantity

AI algorithms rely heavily on access to high-quality, well-curated datasets for training and validation of AI algorithms. Currently, a major limitation for further deployment of AI in dentistry is the lack of sufficient and accurate data. Therefore, it is currently the responsibility of dentists to focus on collecting and entering valid data into their database so that it can be fully used for AI in dentistry in the future.11 In dentistry, access to large, diverse datasets with annotated clinical data can be limited, leading to challenges in developing robust AI models. Challenges may arise from the fragmentation and variability of dental data sources, data privacy regulations, and concerns about data security. Additionally, data privacy regulations and concerns about patient confidentiality may restrict the sharing and aggregation of dental data, further complicating efforts to build AI systems. Dentists and AI developers must address these challenges by establishing

data sharing agreements, implementing data governance frameworks, and ensuring compliance with regulatory requirements.[9]

Continual updating of AI-systems

Additionally, maintaining and updating AI systems to keep pace with evolving technology adds another layer of logistical complexity.

AI systems must continually learn and adapt to new data, emerging trends, and evolving clinical practices to remain effective and relevant over time. Dentistry is a dynamic field with constant advancements in technology, materials, and treatment modalities. AI algorithms must be capable of adapting to changes in dental practice guidelines, diagnostic criteria, and treatment protocols to maintain accuracy and efficacy. Implementing mechanisms for ongoing model validation, calibration, and updating will be essential to ensure the long-term performance of AI systems in dentistry.[11,26]

Training and Education

Dentists and dental staff need adequate training and education to understand how to use AI technologies effectively and interpret their outputs accurately. Dental education will need to accompany the introduction of clinical AI solutions by fostering digital literacy in the future dental workforce.[111] Continuous training may be necessary to keep up with advancements and updates in AI.[2] In order to use the advantages of AI correctly, it is important to use these tools with intelligence, objectivity and common sense, with an appropriate learning curve.[101] The road to successful integration of AI into dentistry will necessitate training in dental and continuing education, a challenge that most institutions are not currently prepared for.[17]

Interdisciplinary Collaboration

Successful integration of AI into dental practice will require interdisciplinary collaboration among dentists, computer scientists, engineers, and other healthcare professionals.[11] It has been suggested that an innovative inter-professional coordination among clinicians, researchers, and engineers will be the key to AI development in the field of dentistry.[13] Challenges may arise from differences in terminology, expertise, and priorities among stakeholders. Dentists may lack the technical expertise to develop and deploy AI systems independently, necessitating collaboration with experts in machine learning, data science, and software engineering. Establishing collaborative networks and partnerships between dental schools, research institutions, and technology companies will be crucial for advancing the field of AI in dentistry and translating research into clinical practice.

Ethical Considerations

Among the great challenges posed to democracy today is the use of technology, data, and automated systems in ways that threaten the rights of people.[102,103] It is suggested that there is a lack of regulatory oversight, especially with the use of facial images, and a urgent need to establish licensing protocols, and the imperative to investigate the moral quality of new norms set with the implementation of AI applications in medico-dental diagnostics.[104]

Conscientious and ethical AI use in dentistry has to consider: (i) when to apply AI and (ii) how to use AI appropriately and responsibly. Patients should be notified about how their data is used, also about the involvement of AI-based decision-making, especially if there is a lack of regulatory policy if AI is utilized to diminish costs rather than improve the health of patients, or if the dentist has a conflict of interest. As many dentists are speeding in the direction of integrating AI systems into diagnostics, prognostics, dental treatment, and practice management, the legal and ethical questions are becoming even more pertinent.[14,65,81,103,105-108]

Patient Privacy and Data Security

AI systems in dentistry often rely on access to sensitive patient data, including medical records, facial images, diagnostic images, and treatment histories. Ensuring the privacy and security of patient information is paramount to maintaining patient trust and compliance with ethical principles.[11,14,65,102,104,106,108] Dentists and AI developers must implement robust data encryption, access controls, and data anonymization techniques to protect patient confidentiality and prevent unauthorized access or disclosure of personal health information.[102,103,105]

Informed Consent and Patient Autonomy

Patients have the right to be informed about the use of AI technologies in their dental care and to provide informed consent for their participation.[14,65,102,104,106,108] Dentists must educate or disclose to patients the capabilities, limitations, and potential risks of AI systems, allowing them to make informed decisions about their treatment options. Respecting patient autonomy and preferences is essential to maintaining trust and transparency in the dentist-patient relationship.[65]

Algorithm Bias and Fairness

AI algorithms may exhibit biases or limitations in their ability to generalize findings across diverse patient populations, dental conditions, and clinical settings, leading to disparities in diagnosis and treatment recommendations.[2,14,48] Accordingly, biases may arise from imbalanced training data, algorithmic assumptions, or inherent limitations of the machine learning models.[9,48,65,109]

As a result, AI systems may perform differently across diverse patient demographics or fail to generalize to new cases not encountered during training, leading to potential disparities in diagnosis and treatment recommendations. Dentists and AI developers must mitigate algorithmic biases by ensuring representative and inclusive training datasets, evaluating model performance across diverse demographic groups, and implementing mechanisms for fairness and accountability in algorithmic decision-making.[102]

Professional judgment, oversight and responsibility

While AI technologies can augment clinical decision-making and assist dentists in diagnosis and treatment planning, they should not replace human judgment or override professional expertise. Dentists remain ultimately responsible (accountable) for the care and well-being of their patients, and must exercise clinical judgment and oversight when using AI systems.[65,106,108] Implementing safeguards such as peer review, quality assurance protocols, and second opinions can help mitigate risks associated with over-reliance on AI. Dentists have a professional responsibility to ensure that AI technologies are used ethically and responsibly in patient care.[14,65,103,106,108] This includes ongoing monitoring and evaluation of AI systems, transparency about their limitations and capabilities, and a commitment to providing high-quality, patient-centered care.[106] Furthermore, dentists have a clear responsibility for AI-generated decisions and outcomes, especially in cases where errors or biases may occur.

Ethical AI Design and Governance

As AI technologies become more pervasive in dentistry, ensuring ethical design, deployment, and governance of these systems will be paramount.[102] Dentists and AI developers must prioritize ethical principles such as beneficence, non-maleficence, autonomy, and justice in the design and implementation of AI algorithms. Transparent and accountable AI systems that prioritize patient safety, privacy, and equity will be essential for building trust among patients, practitioners, and regulatory authorities.[102] The complexity and unpredictability of AI algorithms call for cautious implementation and regular manual validation. Continuous AI learning, proper governance, and addressing privacy and ethical concerns are crucial for successful integration into dental practice.[33,65,103,106,107]

Addressing these ethical considerations is crucial for the responsible and ethical integration of AI into dental practice, ultimately aiming to enhance patient care while upholding ethical standards and principles. Implementing transparent and accountable AI systems, promoting patient-centered decision-making, and maintaining open communication with patients will be essential to address ethical concerns and build trust in AI-driven dental practice.

Legal Considerations

From a legal standpoint, there are questions about liability and accountability in cases where AI systems make errors or fail to provide accurate diagnoses or recommendations. Dentists may need to navigate regulatory frameworks related to medical devices and data protection laws, ensuring compliance with relevant regulations. Liability issues may arise if AI systems make errors or if their recommendations are not followed. Additionally, dentists must navigate intellectual property rights when using AI software developed by third parties. Clear contracts and agreements should outline responsibilities and liabilities.

Regulatory Compliance:

The use of AI in dentistry raises complex regulatory and ethical questions related to patient privacy, informed consent, liability, and professional responsibility.[2,65,104,106,] Regulatory bodies such as the Health Professions Council of South Africa (HPCSA) and professional organizations such as the Dental Association of South Africa (DASA) may need to develop guidelines and standards for the ethical use of AI in dentistry, addressing issues such as data privacy, algorithm transparency, accountability, and patient autonomy. Dentists and AI developers must navigate these legal and ethical considerations to ensure compliance with existing regulations and uphold the highest standards of patient care.

The use of AI in dentistry is subject to regulatory requirements and standards governing medical devices, data privacy, and professional practice. Dentists and AI developers must ensure compliance with relevant regulations such as the South African Protection of Personal Information Act (POPIA), the data protection law of South Africa that safeguards the integrity and sensitivity of private information. It defines what personal data is and prescribes duties for controllers and processors, and medical device

regulations enforced by regulatory agencies such as the Medical Devices Unit of The South African Health Products regulatory Authority (SAHPRA) regulates the licencing of medical device establishments and the registration of medical devices in South Africa to ensure the availability of medical devices that comply with an acceptable level of safety and quality. Dentists and AI developers must navigate these legal and ethical considerations to ensure compliance with existing regulations and uphold the highest standards of patient care.[9] Failure to comply with regulatory requirements may result in legal sanctions, fines, or penalties.

Liability and Malpractice:

Dentists may face legal liability for errors, omissions, or negligence in the use of AI technologies in patient care. While AI systems can enhance diagnostic accuracy and treatment planning, they are not infallible and may produce false positives or false negatives. The question raised here is would a detrimental treatment based on an incorrect prediction of an AI-software be charged for medical malpractice (i.e., the dentist) or product liability (i.e., the company)?65,104 Dentists must exercise due diligence in the selection, validation, and use of AI systems. Dentists may be held accountable for the consequences of AI-driven decisions and interventions.

Intellectual Property Rights:

AI technologies in dentistry may involve the development and deployment of proprietary algorithms, software, and data analytics platforms. The question however, is: who owns the data of a continuously evolving AI software? And may the owner dispose of the data freely?[104] Dentists and AI developers must be mindful of intellectual property rights, including patents, copyrights, and trade secrets, when creating, licensing, or distributing AI systems. Protecting intellectual property assets can safeguard against unauthorized use, reproduction, or distribution of AI technologies by competitors or third parties.

Standard of Care:

The integration of AI into dental practice may also raise questions about the appropriate standard of care and professional competence expected of dentists.[110] Dentists must stay abreast of developments in AI technologies, undergo training and education on their use, and adhere to professional standards and guidelines established by dental associations and regulatory bodies. Failure to meet the standard of care in the use of AI may result in allegations of professional misconduct, negligence, or malpractice.

Conclusion

AI is poised to revolutionize dental practice, offering innovative solutions to enhance patient care and communications, optimize treatment outcomes, streamline practice management, enhance the overall patient experience and promote professional training and education. However, the impact of technological transformation due to the integration of AI over the next decade is perceived by dental professionals, corporate, and health care administrators with a mixture of optimism and cautious anticipation.

The integration of AI in dental practice has seen significant advancements with a range of applications currently being utilized in various aspects of dental care, including AI-powered diagnostic imaging tools that assist in the early detection of oral diseases, personalized treatment planning based on patient data, and virtual simulations for procedure planning and training. However, applications that have reached full clinical maturity and regulatory approval are still very limited.

Key emerging trends and future directions include the development of AI-driven clinical decision support systems, predictive analytics for oral health outcomes, tele-dentistry and remote monitoring, robotics for guided precision procedures, and AI-enabled patient and dental professional education through virtual reality engagement platforms. By leveraging AI technologies, dental professionals will be empowered to unlock new opportunities for precision dentistry, personalized treatment planning, clinical decision support systems, proactive patient engagement and communication, improving practice management to enhancing workflow efficiency and productivity and continuing education.

Thus, while the integration of AI in dental practice holds great promise for improving patient care and outcomes, it also poses various logistical, ethical, and legal challenges and complexities that need to be carefully addressed.

From a practical and logistical point of view, there are concerns about the accuracy and reliability of AI algorithms, as well as the need for extensive training and education for dental professionals to effectively utilize AI technologies, issues related to data management, compatibility of AI systems with existing dental software, and the costs associated with implementing and maintaining AI solutions in dental practices. There will be a learning curve for dental practices to integrate AI technologies into their existing workflows. Adequate training and change management

will also be crucial to adapt to AI driven technological transformations.

Ethically, there are considerations regarding patient privacy and consent, as well as the potential for bias in AI algorithms that could disproportionately affect certain patient populations. Because AI systems handle sensitive patient data, ensuring robust data security and privacy measures will be paramount to maintain patient trust and comply with regulations. Additionally, there are concerns about the role of AI in decision-making and whether it may replace human judgment or autonomy in dental care. From a legal standpoint, there are questions about liability and accountability in cases where AI systems make errors or fail to provide accurate diagnoses or recommendations.

Overall, while there is significant enthusiasm about the potential of AI to revolutionize dental practice, successful implementation will depend on addressing these challenges and ensuring that the technology is used to complement, rather than replace, the expertise and judgment of dental professionals. The initial investment in AI technologies might be substantial, posing a barrier for smaller practices. Ensuring these innovations are accessible to all practice sizes will be important for widespread adoption.

Although the application of AI has numerous advantages, facilitations and optimizations in the dental practice setting, it also has some potential disadvantages including concerns related to job displacement, privacy and security of patient data, lack of transparency and accountability, dependence on technology for clinical decision making, lack of human contact, and that AI systems may have limited understanding of context and have difficulty understanding nuances and subtleties of human language and behaviour.

Continued research, collaboration, and regulation are essential to continue validating the reliability and practicality of AI for possible widespread integration into daily clinical practice, and to ensure that AI technologies are ethically deployed, effectively utilized, and seamlessly integrated into dental workflows while upholding patient safety, privacy, and autonomy. The use of artificial intelligence in dental practice holds immense promise for advancing precision dentistry, driving innovation, and shaping the future of oral healthcare.

Limitations concerning the practical clinical use of AI needs to be addressed in future studies. It is of high importance to continue validating the reliability and practicality of AI for possible widespread integration into daily clinical practice. Further studies are needed to explore specific applications and real-world scenarios before confidently integrating these models into dental practice.

However, the road to successful integration of AI into dentistry will necessitate training in dental and continuing education, a challenge that most institutions are not currently prepared for.

Post script – Recommendations for Use of AI-assisted technologies (language models) in Dental Scholarly Publishing

According to a new announcement from the International Committee of Medical Journal Editors (CMJE), researchers may use AI language models (ChatGPT and BingChat) to write and revise scientific manuscripts.

Chatbots (such as ChatGPT) should not be listed as authors because they cannot be responsible for the accuracy, integrity, and originality of the work, and these responsibilities are required for authorship (see Section II.A.1).

Authors should not list AI and AI-assisted technologies as an author or co-author, nor cite AI as an author."

Artificial intelligence and AI-assisted technologies must not be cited as a reference or other primary source or as an author of a reference.

Authors should carefully review and edit the result because AI can generate authoritative-sounding output that can be incorrect, incomplete, or biased.

Authors should disclose any use of artificial intelligence (AI)–assisted technologies (e.g., large language models, chatbots, image creators) in any aspect of the creation of the submitted work, in the methodology, or Acknowledgement section of the manuscript.

Researchers/ Authors of publication must denote how AI-assisted technologies were used.

Authors who use such technology should describe, in both the cover letter and the submitted work in the appropriate section if applicable, how they used it. For example, if AI was used for writing assistance, describe this in the acknowledgment section (see Section II.A.3). If AI was used for data collection, analysis, or figure generation, authors should describe this use in the methods (see Section IV.A.3.d).

Authors must be able to assert that there is no plagiarism in the article, including in text and images produced by AI-assisted technologies, and must ensure appropriate attribution of all material, including full citations where appropriate.

Human authors are responsible for any submitted material that includes the use of AI-assisted technologies, including its correctness, completeness and accuracy.

Even if AI-assisted technologies are used in a manner in

which manuscript confidentiality can be guaranteed, peer reviewers who choose to use such technologies to facilitate their review must disclose their use and its nature to Editors and are responsible for ensuring that any AI-generated content incorporated into reviews is correct, complete and unbiased.

Reference

International Committee of Medical Journal Editors (ICMJE). Recommendations for the conduct, reporting, editing, and publication of scholarly work in medical journals. International Committee of Medical Journal Editors; updated May 2023. Available: https://www.icmje.org/recommendations/ (accessed 29 March 2024).

References

The full list of References 1-111 is available in the separate References file.