The Role of Artificial Intelligence in Modern Dentistry: Transforming Diagnosis and Treatment Planning

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ABSTRACT

Integrating artificial intelligence (AI) in dentistry transforms clinical practices, enhancing diagnostics, treatment planning, and operational efficiency. This article explores the role of AI in dental care, focusing on its applications, benefits, challenges, ethical considerations, and future innovations. A comprehensive review of recent literature highlights AI advancements in diagnostic imaging, robotic-assisted surgeries, tele-dentistry, and personalized treatment strategies. AI improves clinical decision-making, streamlines workflows, and enhances patient care through precision and customization. However, challenges such as high costs, ethical concerns, and legal accountability issues limit widespread adoption. Strategic investments in AI education, regulatory frameworks, and collaboration among stakeholders are essential for fully leveraging AI's potential. Future innovations promise a more predictive and patient-centered approach to modern dentistry.

Keywords: Artificial intelligence in dentistry, Dental diagnostics, Treatment planning, Ethical considerations in AI, AI challenges in dentistry

Introduction

Integrating advanced technology in dental healthcare has significantly transformed clinical practices, diagnostics, and patient care management. These developments have been propelled by artificial intelligence (AI), which is already changing the delivery of care by dentists when diagnosing, treating, and managing many disorders. AI systems use machine learning (ML) techniques, deep learning models (DL), and neural networks (NN) to provide clinical decision-making support, which used to rely on human knowledge.[1,2] It is used to diagnose oral pathology, improve treatment accuracy, and increase organizational effectiveness, making a positive difference in patient care and practice efficiency.[3,4] Caries, periodontal diseases, and even some types of oral cancer have been diagnosed more effectively with the help of diagnostic tools based on AI technologies, which use the analysis of radiological images and patients' histories.[5,6] In this case, the abnormality is detected early where it might be difficult to detect under normal assessments done on patients by doctors.[7] The application reaches orthodontic planning, where algorithms can predict each tooth's movement, leading to more efficient treatment.[8] In addition, the applications of AI improve the precision of the technology focused on prosthetic dentistry.[9] Other than diagnostics, AI offers other means of enhancing operability in dental practices whereby a number of tasks like scheduling, billing, and record-keeping are performed by AI, sparing the clinician more time to attend to patients.[10,11] Using AI models, it is possible to extract information about the effectiveness of the treatment and the potential progression of the illness to help individual approaches toward patients and early intervention scenarios.[12,13] However, like any other form of technology integration, AI has its pitfalls, particularly in data privacy and security and the expenses incurred in adopting such technologies.[14]

Purpose of the Study

This study aims to explore the transformative impact of AI in dental healthcare, examining its role in diagnostics, treatment planning, and operational efficiency. AI applications using ML and NN bring changes in the quality of clinical decisions, optimizing time-scheduled procedures and guiding improvements in patient care.[1,2] This research aims to find out how AI solutions help in diagnostics at an initial stage, in treatment processes, and in patient-centered care. Also, it emphasizes the weaknesses of the AI integration, which include data privacy concerns, ethical issues, and implementation drawbacks, although strategies to address these limitations as a means to promoting AI usage optimally in the current dental practice are also described. In conclusion, this scholarly work aspires to offer a comprehensive picture of how AI could be used to enhance dentistry and encourage innovation to develop future dental practices.

Objectives of the Study

This study explores AI applications in dental diagnostics and treatment planning, evaluates its benefits and challenges, and addresses ethical concerns. The analysis also highlights future innovations that could further enhance dental care delivery.

- To explore the applications of AI in dental diagnosis, including its impact on accuracy and efficiency.
- To review the role of AI in treatment planning, such as orthodontics, prosthodontics, and restorative dentistry.
- To evaluate the benefits and challenges of integrating AI technologies in clinical dental practice.
- To analyze the ethical considerations and data security challenges associated with the use of AI in dentistry.
- To identify future directions and innovations in AI that could further enhance dental care delivery.

Methodology

This study employed a literature review approach guided by methodologies from.[15,16] Relevant sources were identified through structured database searches,

applying inclusion/exclusion criteria. The selected literature was critically analyzed to explore AI applications, benefits, challenges, and future innovations in dentistry (Table 1).

Overview of AI in Dentistry

AI has become an essential tool in modern dentistry, revolutionizing the diagnosis, treatment planning, and management of dental conditions. Originally, AI was created for other sectors of the health industry as a whole, yet today, it is explicitly refined for dentistry. The application of AI in dentistry makes use of different algorithms, ML and NN, which provide more precision and understanding of dental procedures.[5] One of the most exciting areas where AI can be applied usefully is diagnostics. However, DL algorithms, including convolutional neural networks (CNN), are used in analyzing dental images like X-rays and CT scans that will help in the early detection of diseases like cavities, periodontal diseases, and oral cancers. Overall, AI has been revealed to be as good as, if not better than, human experts at diagnosing specific ailments.[7] For example, research has shown that AI can be used effectively to

detect even the most complex features that are not captured when a human being examines a particular object. This makes it easier to diagnose patients early and accurately, which is important in increasing their survival rates.[8] AI also takes a front-line role in treatment planning, simulations, and diagnostics. Using patient data, the AI system comes up with the right treatment program that best fits each patient to ensure that the patient has high satisfaction and success rates.[9] For instance, AI-enabled systems are applied in prosthetics, and the systems design a unique dental prosthesis based on a patient's oral anatomy (Figure 1).[10,6]

AI in Dental Diagnosis

AI in dental diagnosis has brought about a paradigm shift in the accuracy and speed of detecting various dental conditions, outperforming traditional diagnostic methods. Modern approaches to the development of AI algorithms based on ML and, in particular, DL have undoubtedly improved the efficiency of analyzing and interpreting dental imaging data, for instance, radiographs, CT scans, and intraoral photos much more accurately and with higher inter-observer concordance than any dental clinician.[11] One area that proved the worth of the AI system is assessing dental caries or tooth decay. Caries diagnosis in the past has been done by examination and radiography; however, these AI systems perform better than the conventional methods in diagnosing early-stage lesions (Figure 2).

Research findings reveal that models made using AI and ML, especially through CNNs, achieve a higher sensitivity and specificity of caries in the radiographs than the traditional diagnostic tools.[12] This ability to detect decay early is very important to the prognosis of the decay and the general well-being of the patient. Not only is AI limited to caries detection, but it can also diagnose periodontal diseases such as gingivitis and periodontitis. When applied to radiographic images, AI can more accurately quantify bone resorption and

Table 1 | Inclusion and exclusion criteria table

| Criteria	Inclusion	Exclusion
Timeframe	Studies published from 2020 onwards.	Studies published before 2020.
Language	Articles published in English.	Articles published in languages other than English.
Relevance	Focused on AI applications in dentistry, diagnostics, or treatment planning.	Studies unrelated to AI or its use in dentistry.
Study Type	Peer-reviewed articles, systematic reviews, and conference proceedings.	Opinion pieces, editorials, and non-peer-reviewed publications.
Accessibility	Full-text articles available online or through academic databases.	Abstract-only or inaccessible full-text articles.
Content Specificity	Studies discussing AI's role in clinical decision-making or patient care.	Studies only mentioning AI without detailed analyses of its role in dentistry.
Ethical Considerations	Articles addressing ethical or data privacy concerns in AI.	Studies not discussing ethical or legal aspects of AI in dentistry.
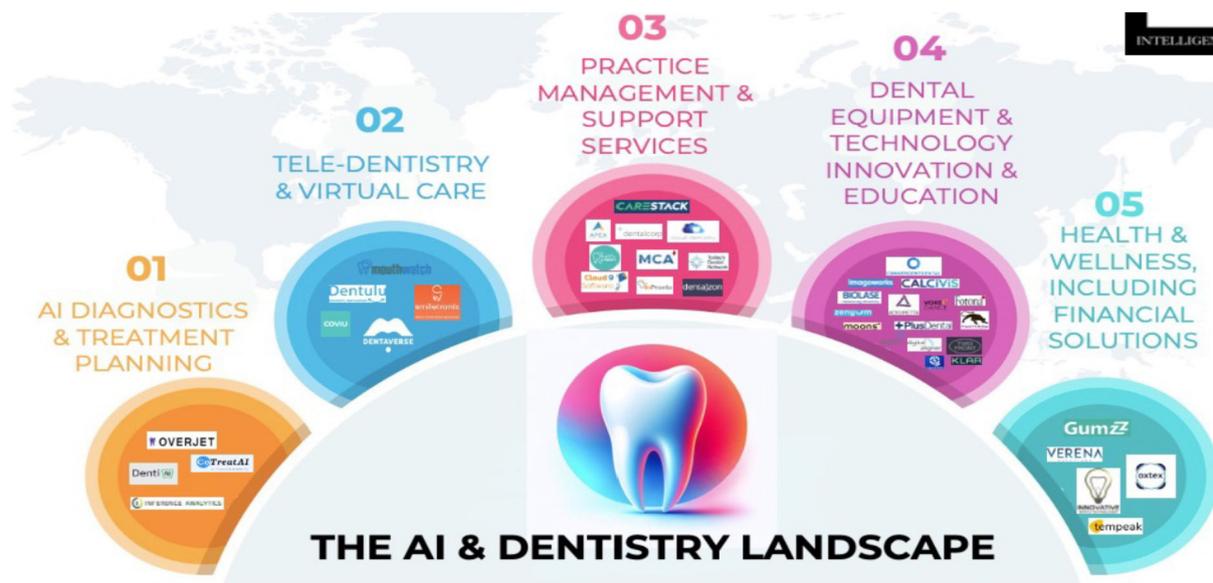
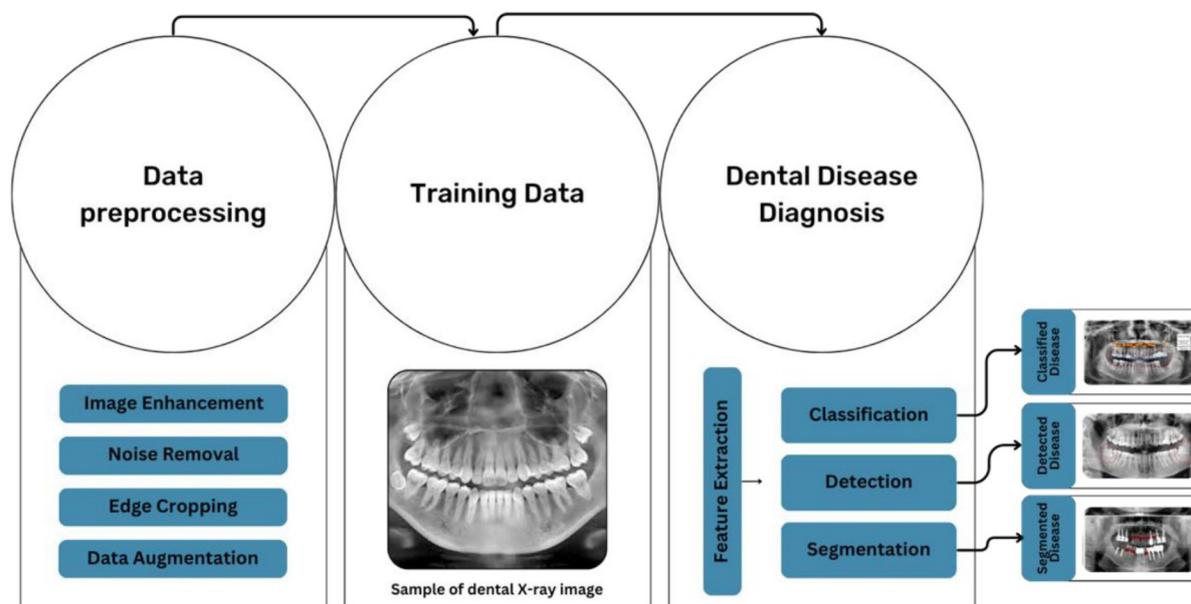Fig 1 | The AI and dentistry landscape by Nissinof (2023)

Fig 2 | Advancing dental diagnostics by Musleh et al. (2024)

Fig 3 | Revolutionizing CAD/CAM-based restorative dental processes by Yeslam et al. (2024)

identify early signs of periodontitis to prompt the necessary intervention and improve outcomes.[13]

Moreover, AI's capacity for oral cancer screening has shown great promise. AI systems can examine images for signs of oral cancer, such as lesions or abnormal tissue changes, with accuracy comparable to, or superior to that of, trained professionals, which is critical for early detection and improving survival rates.[14] These advancements highlight AI's ability to enhance diagnostic workflows in dentistry. By offering higher accuracy, earlier detection, and consistent performance, AI provides significant advantages over traditional diagnostic methods, leading to improved patient care and more efficient treatment planning.[17,18]

AI in Treatment Planning
AI has significantly transformed treatment planning in various dental specialties, bringing greater precision, customization, and efficiency to dental procedures. The most typical use of AI in treatment planning is in the case of orthodontics and more, specifically, the elaboration of aligners. AI can use a 3D scan of the patient's mouth and develop a unique treatment plan that will suit clear aligners. Such algorithms can predict the directions of tooth movement more effectively, which can help enhance the time taken to align teeth and the overall orthodontic treatments. The benefit of such accurate targeting is that patients are provided with the best possible orthodontic solutions and are shown to be more satisfied with the treatment.[19]

In prosthetics, AI pilots the CAD and CAM systems used in designing and manufacturing the prosthesis. As a result of applying this technology, CAD/CAM systems can produce dental prosthetics, such as crowns, bridges, and dentures that are tailored to the unique architecture of each patient's mouth. AI enhances functionality and appearance by analyzing big data, digitally capturing impressions and scans, and finalizing the prosthetic restoration fit. Advancements in CAD/CAM technology integrated with setting AI processing have minimized the human factor intervention, decisions, and time constraints, posing a greater positive impact in prosthodontic treatment delivery than conventional techniques.[20] The complexity level applied in restorative operations is evident, and AI found the optimal method for preparing cavities (Figure 3).

Conventional methods facilitate the identification of the cavities' size and position to recommend the procedure's best strategy. Such systems factor in aspects like the patient's oral status analysis of their dental profile to recommend the most appropriate preparation method. Moreover, the utilization of AI-assisted tools ensures that clinicians carry out cavity preparations to the right measurements that enable sealing and prevent over- or under-preparation, which causes complications. These trends improve the effectiveness of restorative treatments and extend the benefits of the treatment for the patients.[21] Overall, AI's role in treatment planning across orthodontics, prosthodontics, and restorative dentistry leads to more precise, customized, and effective care, ultimately improving patient outcomes and enhancing the efficiency of dental practices.[22]

Integration of AI in Clinical Practice

Integrating AI in clinical dental practice has revolutionized workflow management, patient care, and decision-making processes. The recognition that AI tools are now valuable for improving clinical decision-making timeliness has turned advanced decision support systems into essential productivity enhancers. Such systems can, for instance, engage in time-consuming aspects of a practice, including appointment booking, record-keeping, and preliminary diagnosis, and leave more specialized clinical tasks for the personnel.[23] Consequently, AI positively impacts the clinical processes of administration and the means by which tasks are accomplished. One major branch of AI in clinical practice is in the analysis of radiographs. It can determine caries, bone loss, and cystic image changes with minimal procedural time and high identification efficiency compared to human readers (Figure 4).

It emerged that AI systems can deliver diagnostic information with significant precision as opposed to conventional human techniques; in some cases, the precision is similar to that of experienced dentists.[24] Not only does it improve the time spent diagnosing, but it also improves the diagnostic precision, resulting in improved patient life and outpatient care. Real-time decision-making becomes possible for programmers as automated radiographic analysis, which involves programmed decisions, thus enabling immediate and efficient patient interventions. Examples show how the use of AI relates to a fuller picture of integrated dentistry. For example, AI-aided applications have been applied for treatment planning where tooth movements have been predicted in orthodontics and aligners fabricated accordingly.

Fig 4 | AI integration for diagnostic by Iosif et al. (2024)

Benefits and Challenges of AI in Dentistry

Benefits

The integration of AI in dentistry offers numerous advantages, particularly in enhancing diagnostic accuracy and improving patient care outcomes.

Computer-aided diagnosis can accurately diagnose oral images and even identify potentially severe diseases like dental caries, periodontal disease, and oral cancer.[25] Knowing these conditions at even more advanced stages allows clinicians to offer the requisite treatments, increasing recovery rates and minimizing the negative effects of non-treatment. The other impact is that its implementation will enhance the chance of individualized treatment plans. AI and big-data machines then scan multiple patient datasets to develop personalized treatment plans based on individual oral structures and health histories.[26] This individualized approach not only facilitates improved patients' clinical status but also increases patients' satisfaction with care by garnering appropriate care treatments based on their individual status (Figure 5).[27]

Challenges

Despite its potential, the adoption of AI in dentistry presents notable challenges. High implementation costs, including expenses related to purchasing AI systems and upgrading clinic infrastructure, can be prohibitive for many dental practices, particularly smaller ones.[28] In addition, it precipitates the need for training
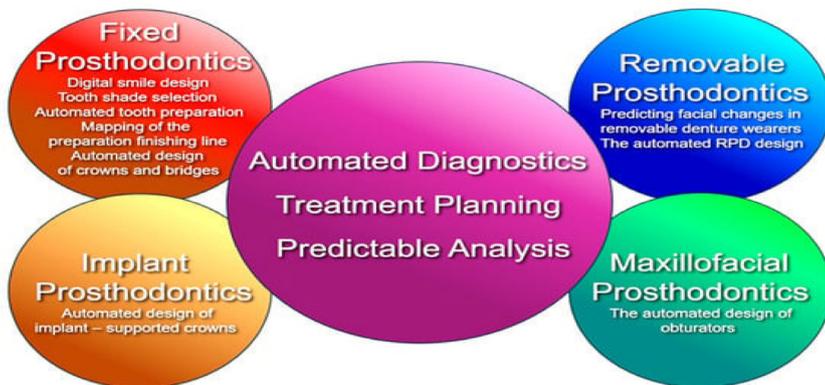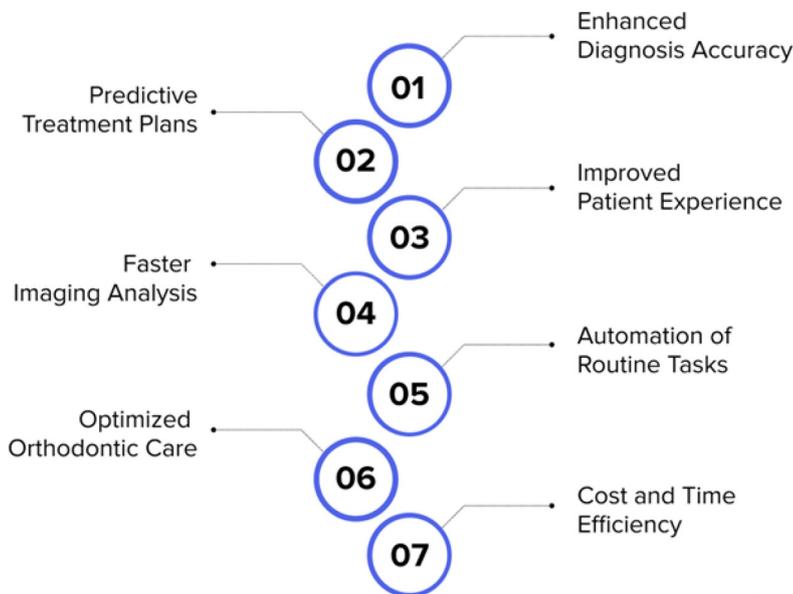

Fig 5 | Advantages of AI in dentistry by Chirag (2024)

dental professionals in using the developed software to operate it and understand insights given by the AI.

This kind of learning curve can deter adoption and restrict the application of AI tools, especially in the short term.[28] Some of the ethical issues that people have with healthcare automation are also depicted with the use of AI in clinical care delivery. Issues concerning legal responsibility for AI choices arise from academic and practical challenges, such as misdiagnosis, inappropriate therapy binding, and ethical considerations[29] (Figure 6).

Ethical and Legal Considerations

The rise of AI in dentistry brings significant ethical and legal considerations, particularly regarding data privacy, security, and accountability. AI systems currently depend on large patient health-related data, such as dental records, medical histories, imaging data, and many others, to enhance algorithm learning and precision.[30] Such dependence creates new risks for the protection of patients' data from access, violations, and unauthorized use. There and then, keeping to data protection laws like the GDPR common in European countries is a paramount factor toward ensuring patients trust their physicians, hence embracing

ethical practice.[30] There are legal implications because patients will sometimes suffer from misdiagnosis or receive a wrong treatment due to the clinical decision support (CDS) (Figure 7).

Accountability models in conventional health systems place the entire responsibility for clinical decisions on the healthcare provider. Nevertheless, where such systems play a role in decision-making or have a significant impact on the decision made, the question of legal liability arises.[31] Due to the fact that AI assumes decision-making on its own, dental practitioners may have immense difficulty in proving negligence where mistakes have been committed. Setting responsibly defined legislation as guidelines to determine AI's beneficiary/plaintiff/defendant relationships is crucial to managing such risks.[31] Ethical issues are not limited to patient data used in AI learning and system designing processes only. It thus became important for patient's consent to be obtained, especially when data is used outside the realm of the actual treatment of the patient.[12]

It is essential to clearly explain how AI-based systems use patient information and ensure that the data is used in a way that benefits the patients.[21] Further, the strategies should include measures that minimize bias in the AI system and that could prevail in the
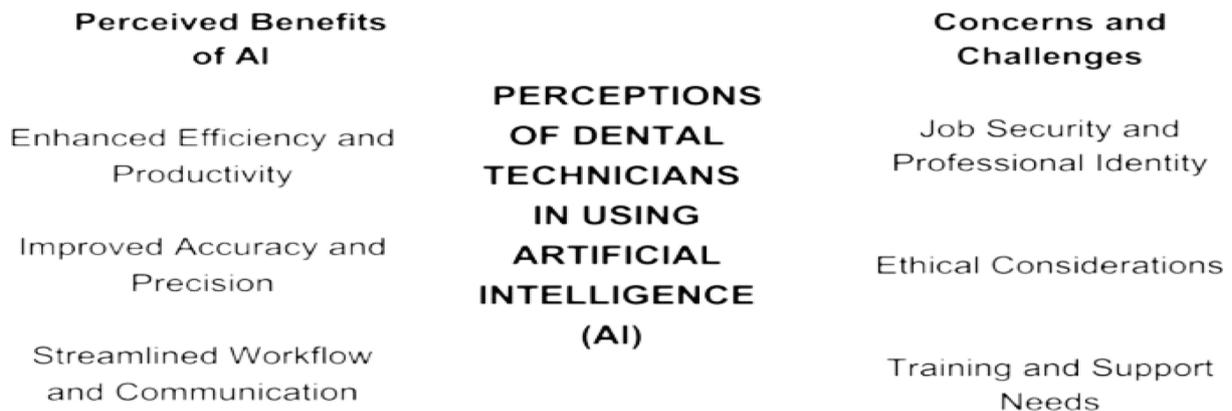

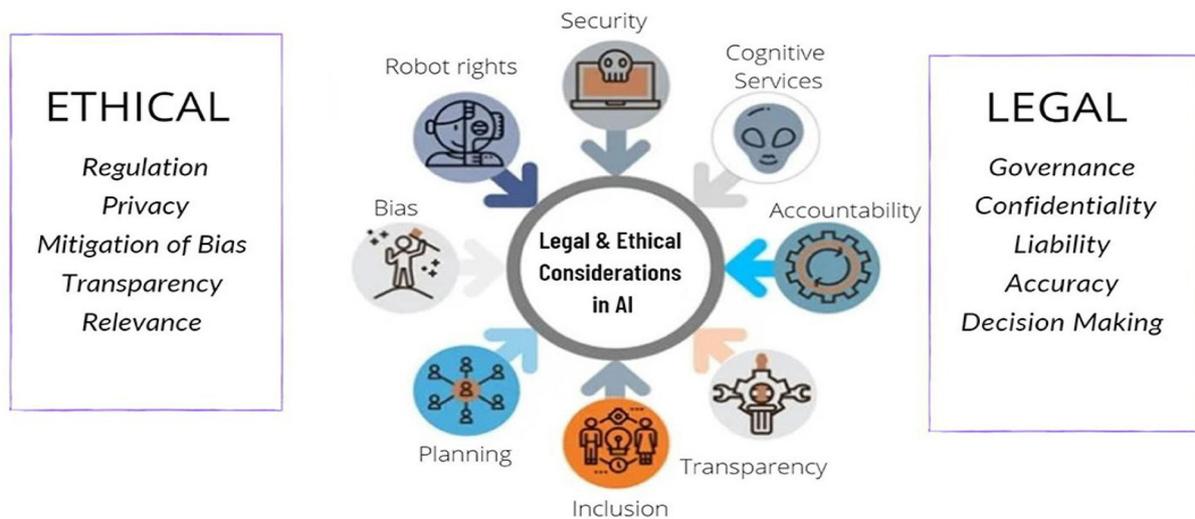Fig 6 | Benefits and challenges of AI in dentistry by Ng Lin et al. (2023)

Fig 7 | Ethical and legal considerations of AI in healthcare by Naik et al. (2022)

diagnosis of the disease or perpetuation of disparities in the delivery of healthcare. Solving these ethico-legal concerns thus calls for effective interaction between the dental workers, the algorithm developers, jurists, and legislators in the establishment of appropriate guidelines that will sufficiently safeguard the patient's interests, while at the same time IR4 facilitating the use of technology in dental procedures.[30,31]

Future Directions and Innovations

The future of AI in dentistry is poised for transformative developments, driven by innovations such as robotic-assisted surgeries, advanced imaging technologies, tele-dentistry, and wearable devices. These developments are revolutionizing the dental healthcare delivery system and opening it to more efficiency, accessibility, and specificity.[7] Robotic-assisted surgeries can be counted as a novel leap in the advancements offering precise outcomes to intricate dental operations like implants and maxillofacial surgeries. By incorporating AI, robotic systems can study patient data and navigate surgical instruments with great care, thus reducing the error rate in the procedures.[17] In the same way, improved topographical diagnostic techniques, 3D imaging, and cone-beam computed tomography with integrated AI enhance accurate diagnostic outcomes. Such technologies enable clinicians to have improved visibility of the oral structures and, hence, improved treatment plans and results.[7]

Tele-dentistry technologies and applications have steered the process of creating more dental care opportunities with the help of AI. Virtual assistants utilizing AI can categorize patient concerns, arrange appointments, and make a preliminary diagnosis, thus making it easier for the patient to receive healthcare and address the health's social determinants.[25] Moreover, wearable solutions with AI integrated into their platform are being designed to track oral health in near real time. Such devices can gather information about salivary pH, plaque index, oral behavior and habit and, therefore, precious information for the management of preventive and clinical processes.[32] This work established that there is a need for more research and development relating to the application of AI in dentistry. New innovations in ML, NN, big-data analytics will make the AI system even smarter and more competent.[33] Realization of recent advancements in AI requires joint efforts from dental professionals, AI developers, and researchers due to the highly specialized nature of this sector of healthcare and to enable future-generation technologies to enhance efficiency in dental healthcare and improve patient care and outcomes.[27]

Conclusion

The integration of AI into dentistry is revolutionizing how dental care is delivered, enhancing diagnostic precision, treatment planning, and operational efficiency. Technologies such as ML, robotic surgeries, and imaging techniques are shaping the high accuracy of diagnosis methods and giving increased possibilities of precise treatment for individual patients. They have enhanced therapeutic choices and patient outcomes and

minimized paperwork and transactional work. Moving forward, the future of AI implementation entails drawing future research and technological and infrastructural integrations with reference to the AI-enhanced care models. Education on AI and encouraging technological readiness will ensure dental professionals are ready and in a position to fully exploit the usefulness of the technologies at their disposal. In this way, the dental field can implement stronger, more accurate, as well as even more individualized patterns of occurrence, prevention, and treatment, which will build the future of contemporary dentistry. The integration of AI into dentistry is revolutionizing how dental care is delivered, enhancing diagnostic precision, treatment planning, and operational efficiency. AI technologies such as ML algorithms, robotic-assisted surgeries, and advanced imaging tools are redefining diagnostic accuracy and offering more personalized treatment options. These advancements have improved clinical decision-making and patient care while streamlining administrative processes.

Novel Contributions

This research presents the prospect of incorporating the use of AI-based AR technology in visualizing surgeries to enable high accuracy and better results in dental surgeries.[10] Moreover, there are enormous application opportunities in prosthodontics since the use of generative AI models can help create personalized dental implants more efficiently and thereby improve treatment outcomes.[22]

Practical Recommendations

AI should also be implemented as a tool, such as intraoral scanners, for better image resolution for dental practitioners.[3] Decision-makers should ensure telecommunications is invested in tele-dentistry platforms utilizing AI for remote and improved dental care utilities in regions with limited access.[17]

Global Relevance

These challenges include significant costs associated with implementation and legal restrictions that remove an AI solution from its supportive environment for a considerable amount of time in low-resource countries.[6] Governments and NGOs should do research to ensure that they come up with affordable AI resources and then proceed to support AI-based training programs. AI solutions must be open-source to extend people's dental healthcare access globally.[5]

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