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Shaping Smiles: The Evolution and Future of AI in Dentistry

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ABSTRACT- Artificial Intelligence (AI) has emerged as a revolutionary force in various sectors, particularly in healthcare, where its integration into dentistry is making a significant shift in clinical practice. This article provides and overview of the fundamentals of AI, distinguishing between weak and strong AI, with a focus on the applications of weak AI in dentistry. Weak AI, which is predominant today, includes specialized systems for tasks such as image recognition and natural language processing, while strong AI seeks to replicate human-like general intelligence. A significant aspect of weak AI is machine learning, further categorized into supervised, unsupervised, and semi-supervised learning, with deep learning—especially through Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs)—exhibiting exceptional capabilities in analyzing dental images and generating synthetic data. The article also explores various applications of AI in dentistry, including diagnostic assistance, treatment planning, patient management, and predictive analytics, highlighting the benefits of improved accuracy and efficiency in clinical decision-making. Additionally, it discusses the future scope of AI in dentistry, emphasizing its potential to enhance personalized care, streamline workflows, and transform patient outcomes. As AI continues to grow, its use in dentistry could lead to major advancements, bringing a new wave of technology to oral healthcare.

I. INTRODUCTION-

Artificial intelligence (AI) is the technology that utilizes machines to mimic intelligent human behavior. It is the process of training a computer in such a way that it starts thinking like human beings[1].Defined as the theory and development of systems capable of performing tasks that typically require human intelligence—such as visual perception, speech recognition, and decision-making—AI is transforming industries like robotics, automotive, finance, and healthcare[2]. AI encompasses the study of systems enabling computers to perform tasks that typically require human intelligence, with the ultimate aim of enhancing utility and understanding the underpinnings of intelligence. Artificial Intelligence (AI) has emerged as a transformative force across various sectors, and its integration into healthcare, particularly dentistry, marks a significant evolution in clinical practice.

In the medical field, AI applications are growing in areas such as imaging diagnostics, decision support, and precision medicine. In dentistry, AI is being utilized across various disciplines—operative dentistry, orthodontics, periodontics, oral surgery, and prosthodontics and can help by promising significant improvements in diagnostic accuracy and treatment planning[3,4]. This cross-disciplinary capability underscores the potential of AI in enhancing diagnostic accuracy and treatment planning in dental practice[5]. However, this integration also raises complex ethical challenges, particularly concerning diagnostic variability and the subjectivity of treatment decisions [6,7].

This article aims to review the current scenario of AI in dentistry, focusing on its applications, strengths, weaknesses, and challenges and the role it can have in future. The importance of this exploration is underscored by the increasing volume of literature highlighting AI's role in diagnosing oral diseases, formulating individualized treatment plans, and enhancing surgical precision. While there are previous studies focusing on technical analyses, this review seeks to present AI's implications in accessible terms for dental professionals discussing its applications, strengths, weaknesses, and the relationship between Evidence-Based Dentistry (EBD) and AI. By addressing the research questions like trends and

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applications, strengths and weaknesses and the challenges that lie ahead, this article endeavors to illuminate the future trajectory of dental research influenced by AI innovations.

History and Classification of Artificial Intelligence

Artificial Intelligence (AI) is a well-established concept that traces its origins back to the mid-20th century, but its practical applications have accelerated over the last two decades due to advances in big data, computational power, and sophisticated algorithms.Alan Turing, in his influential 1950 paper "Computing Machinery and Intelligence," proposed that machines could exhibit intelligent behavior, suggesting that by the end of the century, people would accept the belief of machines "thinking" [8.]

In 1956, the term "Artificial Intelligence" was formally coined during the Dartmouth Summer Research Project, led by John McCarthy and others[9]. However, early AI research faced significant limitations, including a lack of storage capabilities in computers and inadequate funding, which stifled practical advancements. Despite these challenges, the field began to grow between 1957 and 1974, fueled by increasing computational power and improved algorithms. Notable early programs included ELIZA, which simulated conversation[10].

AI experienced setbacks during two periods known as "AI Winters," primarily due to diminished funding and a lack of successful applications[11]. Nevertheless, the 1980s saw a resurgence, characterized by two distinct paths: machine learning (ML) and expert systems. While ML enables systems to learn from data, expert systems rely on pre-programmed rules to mimic human decision-making processes[12].

The evolution of AI accelerated significantly with the advent of deep learning (DL) and neural networks in the 2010s. Milestones include a DL model winning the ImageNet competition in 2012[13] and Google's AlphaGo defeating a world champion in Go in 2017 [14].

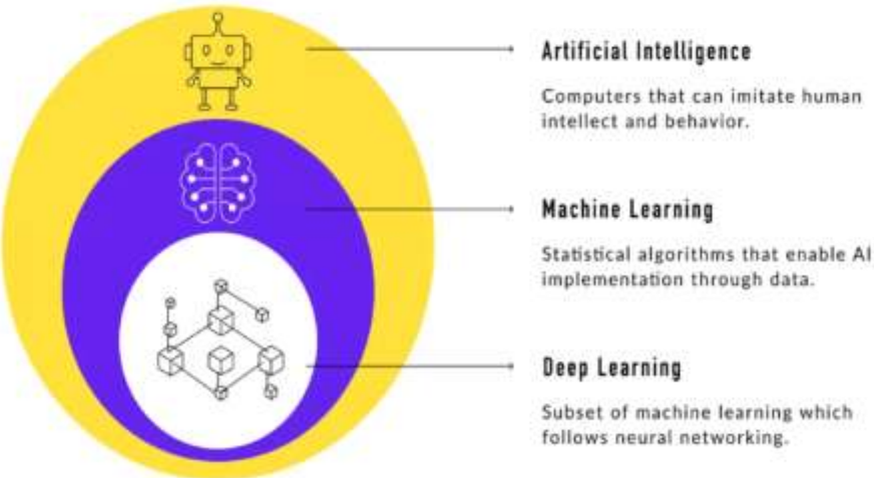

Figure 1. Artificial intelligence

AI can be classified into weak AI and strong AI. Weak AI, which predominates today, is designed for specific tasks (e.g., image recognition, natural language processing), while strong AI aims to replicate human-like general intelligence[15]. Within weak AI, machine learning can be further divided into supervised, unsupervised, and semi-supervised learning. Deep learning, a subset of machine learning, employs neural networks to autonomously extract features from large datasets. Variants such as Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs) have shown remarkable effectiveness in tasks like image recognition and data generation[16].

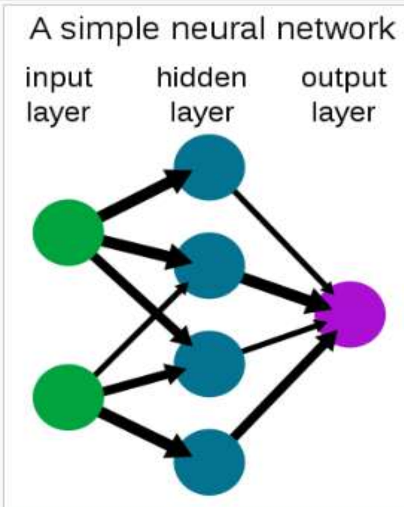

Figure 2 Deep learning

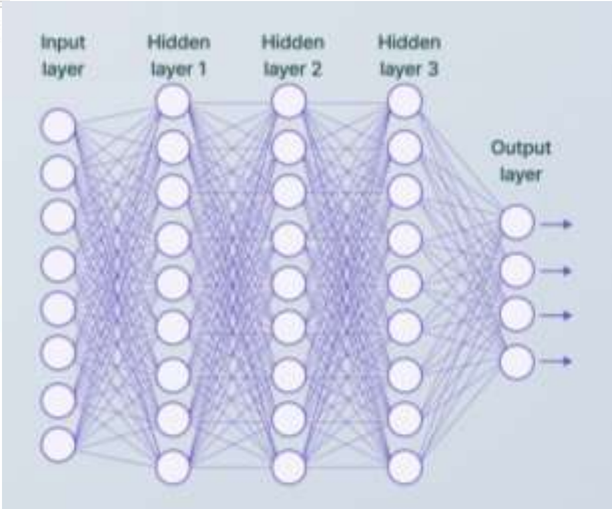

Figure 3- Convolutionalneural network

Type of AI	Description	Subcategories	Examples
Weak AI	Designed for specific tasks (e.g., image recognition, natural language processing)	Supervised Learning	Image classification
		Unsupervised Learning	Clustering data
		Semi-Supervised Learning	Combining labeled and unlabeled data
		Deep Learning	Neural networks
Strong AI	Aims to replicate human-like general intelligence		N/A
Deep Learning	A subset of machine learning that uses neural networks to autonomously extract features	Convolutional Neural Networks (CNNs)	Image recognition
		Generative Adversarial Networks (GANs) Data generation	Data generation

Table 1. Classification of AI

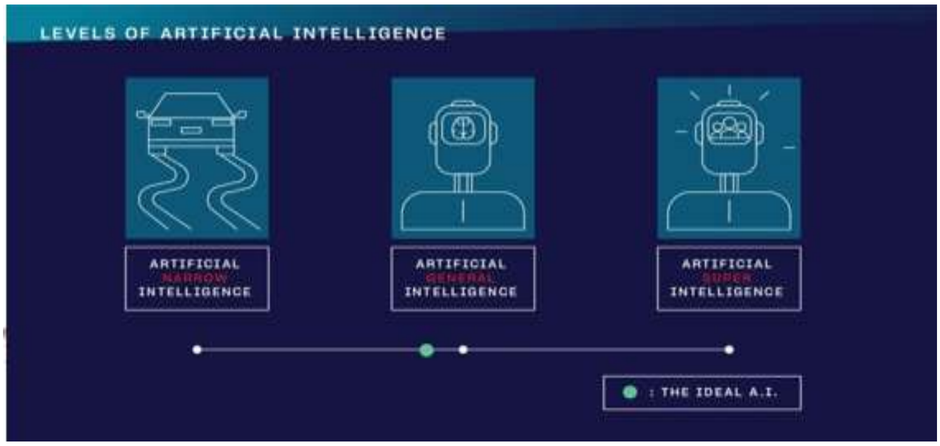

Figure 4- Levels of AI

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The various levels of AI include –

Narrow AI (Weak AI) performs specific tasks, like voice recognition or recommendations, without understanding beyond its function.

General AI (Strong AI) possesses human-like cognitive abilities, allowing it to learn and apply knowledge across various domains.

Super-intelligent AI exceeds human intelligence in all aspects, including creativity and problem-solving, but remains a theoretical concept.

So, AI has evolved from theoretical foundations to practical applications, shaping a diverse landscape of technologies that continue to transform various sectors.

Applications of AI in Dentistry

Artificial Intelligence (AI) has transformed various sectors, particularly healthcare. In dentistry, AI enhances diagnostic capabilities, optimizes treatment planning, and improves patient outcomes through technologies like robotic systems, diagnostic aids, and data analysis (Kumar & Jain, 2021[17]; Liu et al., 2022)[22]. There are certain applications which are common to all specialties of dentistry while certain specific to each specialty.

1. AI in Diagnostic Assistance

AI's most notable application in dentistry lies in its diagnostic capabilities. AI significantly improves diagnostic accuracy by analyzing medical images. Several studies demonstrate AI's effectiveness in identifying oral diseases, such as caries, periodontal disease, and oral cancers. For instance, a systematic review by Ghaffari et al. (2020)[18] highlighted that deep learning algorithms could achieve diagnostic accuracy comparable to human specialists. Traditional methods, such as expert systems, are evolving into deep learning models that leverage extensive datasets, particularly digital radiographs, to detect dental diseases more accurately (Bengio et al., 2013[19]; LeCun et al., 2015[20]). Similarly, Esteva et al. in 2019[21] reported AI's potential to analyze radiographic images, improving early detection rates of malignancies. Machine learning algorithms, such as Support Vector Machines (SVM), facilitate the identification of systemic conditions by efficiently processing electronic medical records, aiding dentists in recognizing congenital abnormalities and other complex conditions. State of the art technologies like Artificial Neural Networks (ANNs) and Convolutional Neural Networks (CNNs) are integral to AI in dentistry. These models analyze large datasets to improve disease detection, such as identifying oral cancers through imaging (Liu et al., 2022)[22]. CNNs, in particular, are well-suited for processing visual data, making them ideal for radiographic analyses (LeCun et al., 2015)[20].

2. Treatment Planning and enhanced patient care

AI also plays a crucial role in treatment planning. By analyzing patient data, AI applications in dentistry are primarily designed to support clinical decision-making. AI can suggest personalized treatment options, enhancing clinical outcomes. A study by Sivaraman et al. (2021)[23] indicated that AI algorithms could recommend individualized orthodontic plans, improving patient satisfaction and treatment efficiency. Clinical decision support systems use algorithms to provide dentists with data-driven insights for treatment options. This reduces human error and improves the efficiency of care (Rojas & Garcia, 2018)[24]. Furthermore, Gupta et al. (2020)[25] emphasized AI's utility in the design and customization of dental prostheses. AI can analyze patient history and predict future oral health issues, enhancing personalized care and precision medicine (Gonzalez et al., 2021)[26].

3. **Data Management**: AI analyzes electronic medical records and scientific datasets, improving diagnoses of conditions like congenital abnormalities and assisting in personalized treatment plans.
4. **Automated Systems**: Virtual dental assistants manage administrative tasks, optimize appointment scheduling, and provide reminders for preventive care, allowing dentists to focus more on patient treatment (Figure 2).

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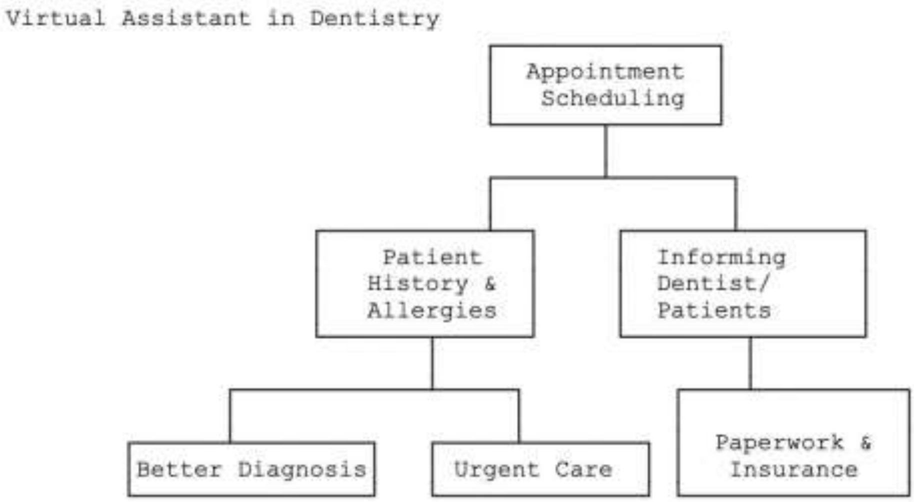

Responsibilities	Description
Appointment Scheduling	Manage patient appointments, send reminders, and reschedule as necessary.
Patient Communication	Handle inquiries via phone, email, or chat; provide information about services and policies.
Dentist communication	About patient allergies and necessary checks based on risk factors before patient visit.
Billing and Insurance	Assist with patient billing, verify insurance coverage, and follow up on claims.
Record Management	Maintain patient records and ensure compliance with HIPAA regulations.
Marketing Support	Assist with social media management, email newsletters, and online reviews to enhance online presence.
Inventory Management	Keep track of dental supplies and place orders as needed.
Telehealth Coordination	Help with scheduling and managing virtual consultations.
Patient Follow-ups	Check in with patients post-treatment to ensure satisfaction and address concerns.

Table 2. Key responsibilities of virtual assistants in dental practices.

5. **Robotic Assistance**: Robotic systems are becoming prevalent in dental surgeries, providing precision and enhancing surgical outcomes. These systems assist in procedures, allowing dentists to focus more on complex aspects of care (Kumar & Jain, 2021)[17].
6. **Simulation experience using Augmented and Virtual Reality**: Augmented Reality (AR) and Virtual Reality (VR) are innovative tools in dental education and patient treatment. These technologies enhance patient experiences by allowing simulations of dental procedures and improved training for dental students.AR overlays digital images onto the real world, helping patients visualize treatment outcomes, while VR provides immersive training environments for dental students. This technology enables safe, simulated experiences, reducing the risks associated with training on live patients (Rojas & Garcia, 2018)[24].

7. Data Mining and Predictive Analytics

Data mining is a critical process that focuses on extracting meaningful patterns and relationships from large datasets, differentiating it from machine learning, which primarily emphasizes predictive modeling. Data mining techniques analyze large datasets to uncover patterns and correlations in dental health, facilitating early detection of conditions like caries and periodontal diseases. In the context of digitized dental data, data mining techniques can uncover significant variations in how different dentists diagnose and predict dental caries and estimate dental age. This analysis not only enhances clinical understanding but also supports standardized practices across the dental field. (Gonzalez et al.,

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2021)[26]. AI systems can also predict patient risks based on historical data, enabling proactive interventions (Liu et al., 2020)[27]. Research has demonstrated that leveraging data mining in dentistry can lead to improved outcomes by facilitating better decision-making based on identified trends and causal relationships (Chaudhary et al., 2017)[28].

8. Future Directions

AI's future in dentistry looks promising, with developments in bioprinting, which could enable the creation of living tissues for reconstructive purposes (Kumar & Jain, 2021)[17]. As AI technology continues to evolve, it will further integrate into all facets of dental practice, from diagnostics to patient management.

Overall, AI in dentistry not only streamlines clinical processes but also enhances patient care through improved diagnostics, treatment personalization, and innovative technologies. Its ongoing integration will likely shape the future landscape of dental healthcare, making it more efficient and effective.

AI in Oral and Maxillofacial Surgery

In oral and maxillofacial surgery, AI technologies provide significant advantages. AI-driven systems can assist in surgical planning and navigation, leading to increased precision and reduced complications. According to Yang et al. (2021)[28], AI algorithms have demonstrated efficacy in predicting surgical outcomes, further establishing their role in enhancing procedural safety and effectiveness.

AI in Operative Dentistry

In operative dentistry, traditional methods for diagnosing caries rely heavily on visual and tactile examinations, as well as radiographic assessments. These techniques can be challenging, particularly for detecting early-stage lesions hidden in deep fissures or tight interproximal contacts. Consequently, many carious lesions are identified only in advanced stages, necessitating more complex treatments such as crowns, root canals, or implants (Schwendicke et al., 2018)[29].

Despite the reliability of dental radiography (including panoramic, periapical, and bitewing views) and exploratory probes, the diagnostic process often depends on the dentist's experience. Recent studies have explored the integration of artificial intelligence (AI) to enhance diagnostic accuracy for various conditions in operative dentistry, including dental caries, vertical root fractures, and pulp space volumetric assessment (Meyer et al., 2019[30]; Lee et al., 2020[31]).

AI algorithms, particularly convolutional neural networks (CNNs), have shown promise in analyzing radiographic images. For instance, Lee et al.[31] developed a CNN to detect dental caries on periapical radiographs, while Kühnisch et al, 2019[32]. applied a similar approach to intraoral images. Schwendicke et al., 2018[29] further demonstrated that AI outperformed traditional dentist diagnoses in terms of cost-effectiveness for proximal caries detection, with results indicating that AI's accuracy is comparable to or exceeds that of human clinicians.

The successful implementation of AI in this field requires interdisciplinary collaboration between computer scientists and dental professionals. Clinicians are involved in manually labeling radiographic images to identify carious locations, while computer scientists develop the machine learning algorithms. Together, they verify the training results to ensure accuracy and precision (Meyer et al., 2019)[30].

AI offers a transformative potential in operative dentistry, particularly for early lesion detection, which can lead to timely interventions and improved patient outcomes. The synergy between dental expertise and advanced computational techniques is crucial for realizing these benefits.

AI in Endodontics

Endodontics, focusing on diseases of the dental pulp and surrounding tissues, is transforming through the integration of Artificial Intelligence (AI). This technology enhances diagnostic accuracy, optimizes treatment planning, and improves patient outcomes.

AI significantly enhances diagnostic capabilities by analyzing complex datasets. Machine learning algorithms can process radiographic images to identify conditions like pulp necrosis and apical periodontitis. Azhari et al. (2022)[33] found that AI models achieved diagnostic accuracy comparable to experienced endodontists in interpreting periapical radiographs. Al-Shahrani et al. (2021)[34] confirmed that AI reliably detects endodontic lesions and aids in differential diagnoses.

AI also improves treatment planning by analyzing patient-specific data, including clinical findings and imaging results. Algorithms can suggest tailored treatment options based on the specifics of each dental condition. Hossain et al. (2021)[35] highlighted AI's role in optimizing root canal treatment plans, leading to better outcomes and fewer errors.

In predictive analytics, AI models utilize historical treatment data to forecast the likelihood of treatment success or failure. Kumar et al. (2021)[17] demonstrated that AI could predict endodontic treatment outcomes, enhancing clinical decision-making.

AI tools, such as chatbots and virtual assistants, improve patient education and engagement, ultimately leading to better adherence to treatment plans (Wang et al., 2023)[35]. As AI technology evolves, its applications in endodontics promise to enhance patient care and practice efficiency.

AI in Periodontics

Periodontitis is a prevalent disease affecting billions worldwide and can lead to tooth mobility and loss if untreated (Kumar et al., 2021)[36]. Early detection and treatment are crucial to prevent severe outcomes. Traditionally, the diagnosis of periodontal disease relies on clinical evaluations such as pocket probing depths and gingival recession, often quantified by the Periodontal Screening Index (PSI). However, this approach can be unreliable, as it heavily depends on the dentist's experience, which may lead to missed localized tissue loss (Gonzalez et al., 2020)[26].

AI has emerged as a valuable tool in periodontics for diagnosing and classifying periodontal diseases. For instance, Krois et al. (2020)[37] utilized Convolutional Neural Networks (CNNs) to detect periodontal bone loss on panoramic radiographs. Similarly, Lee et al. (2021)[31] assessed a CNN algorithm's effectiveness in automatically identifying periodontally compromised teeth. Furthermore, Yauney et al. (2022)[38] developed a CNN algorithm that incorporates systemic health-related data to evaluate periodontal conditions.

So, AI technologies are enhancing diagnostic accuracy in periodontics, offering a promising complement to traditional methods.

AI in Orthodontics

Orthodontic treatment planning traditionally relies on the experience and preferences of orthodontists, making the diagnosis of malocclusion complex and variable (Cui et al., 2020)[39]. The cephalometric analysis involves numerous factors, complicating treatment planning and outcome predictions. However, advancements in Artificial Intelligence (AI) are transforming this process, particularly in landmark identification and treatment planning, which are often tedious for practitioners.

AI has been successfully applied in various orthodontic tasks, including tooth segmentation and classification from radiographs and 3D digital scans. Cui et al. (2020)[39]also developed several AI algorithms that automate tooth segmentation on digital models from intraoral scanners and CBCT images, achieving efficiency rates significantly faster than manual efforts—up to 500 times quicker.

Moreover, AI enhances treatment planning by simulating pre- and post-treatment changes, improving communication between patients and clinicians (Thanathornwong, 2021)[40]. Models like those proposed by Xie et al. (2021)[41] evaluate the necessity for extractions from cephalometric radiographs, while Park et al. (2021)[42] demonstrated deep learning algorithms for accurate identification of cephalometric landmarks.

AI is revolutionizing orthodontics by improving diagnostic accuracy, streamlining treatment planning, and facilitating better patient-clinician communication.

AI in Oral and maxillofacial radiology-

AI has shown significant promise in oral and maxillofacial radiology, particularly through the use of convolutional neural networks (CNNs) for detecting anatomical structures and diagnosing dental conditions. Studies reveal that CNNs can identify and classify teeth in periapical radiographs with an accuracy of 95.8% to 99.45%, closely matching the 99.98% accuracy of clinical specialists. Additionally, a deep CNN algorithm analyzed 3,000 radiographs to detect carious lesions, achieving an accuracy of 75.5% to 93.3% and sensitivity of 74.5% to 97.1%. This represents a notable improvement over traditional radiographic diagnosis, enhancing sensitivity while reducing the reliance on higher radiation doses through artefact reduction algorithms (Bae et al., 2020[43]; Jha et al., 2021[44]).

AI in Oral and Maxillofacial Pathology

Early identification and diagnosis of oral lesions are crucial in dental practice, as timely detection significantly improves patient outcomes, particularly for lesions that may be precancerous or cancerous. Convolutional neural networks (CNNs) have emerged as valuable tools in diagnosing head and neck cancer lesions. Studies show that CNNs achieve specificity of 78% to 81.8% and accuracy of 80% to 83.3%, closely paralleling the performance of specialists, who report specificity of 83.2% and accuracy of 82.9%. This demonstrates the potential of CNNs to enhance diagnostic accuracy in oral medicine and

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pathology, thereby improving treatment decisions and patient care (Zhang et al., 2020[45]; Lee et al., 2021[46]).

Challenges and Ethical Considerations

While the integration of AI in dentistry promises significant improvements in diagnostics and treatment efficiency, it also presents several notable weaknesses. One of the primary concerns is the limited adoption of AI solutions in routine dental practice due to insufficient data, development standards, and ethical considerations (Jha et al., 2021[47]). Additionally, reliance on AI for healthcare decisions raises questions about data misuse and security. Trusting machines to make critical healthcare decisions can be risky, especially if they lack transparency and interpretability (Moussa et al., 2020[48]).

Data management poses a significant challenge as AI systems require vast amounts of patient-specific data for training and validation. This necessitates stringent measures to protect patient privacy and confidentiality, including anonymization, which is often met with skepticism in the healthcare industry (Jha et al., 2021[47]). Moreover, AI systems must adhere to safety protocols to ensure efficacy. The introduction of classifications like "Software as a Medical Device" by regulatory bodies, such as the FDA, aims to address these safety concerns (FDA, 2020[49]).

Another critical issue is the ambiguity of accountability when AI systems make decisions. The legal implications of replacing human judgment with autonomous agents raise ethical dilemmas, complicating responsibility in case of errors or adverse outcomes (Jha et al., 2021[47]). Furthermore, the quality of predictions made by AI heavily depends on the accuracy of training datasets. Mislabeling can lead to poor performance and unreliable outcomes. Therefore, healthcare professionals must understand the AI systems they use and be able to interpret their results effectively[50].

Thus, while AI holds great potential in dentistry for enhancing early diagnoses and alleviating labor shortages, challenges related to data security, interpretability, accountability, and integration into clinical workflows remain significant hurdles to overcome.

II. CONCLUSION-

The integration of AI in dentistry offers transformative potential, enhancing the diagnostic accuracy, personalizing treatment, and improving surgical precision. Despite these advantages, the ethical challenges and the need for adequate training highlight the complexities of this technological evolution. Further research is essential to address these ethical challenges and ensure effective implementation. A collaboration between technologists and dental professionals will be the key to optimize patient care taking into consideration the complexities of AI integration. A balanced approach is the need of the hour for significant improvement in dental healthcare delivery.

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