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Artificial Intelligence In Restorative Dentistry And Endodontics: Current Trends And Future Directions

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Abstract:
***Background**: **Artificial Intelligence (AI)** refers to computer systems that perform tasks requiring human intelligence, such as learning, reasoning, decision-making, and problem solving. **Machine Learning (ML)** is a subset of AI that enables computers to learn from data and improve performance without explicit programming. In dentistry, AI and ML are transforming diagnosis, treatment planning, patient management, and clinical decision making. Artificial intelligence (AI), particularly through advanced algorithms such as convolutional neural networks (CNNs), has significantly improved the analysis of dental imaging, including radiographs and cone-beam computed tomography (CBCT) scans. These AI-driven systems enable precise identification of dental caries, periapical pathologies, and complex root canal anatomies, thereby enhancing diagnostic accuracy. Furthermore, AI assists in clinical procedures such as tooth shade matching and working length determination, reducing operator-dependent errors, improving efficiency, and contributing to more predictable treatment outcomes in conservative dentistry and endodontics. In Conservative Dentistry and Endodontics, these technologies enhance precision, reduce human error, and improve treatment outcomes.*

Key Word: *Applications, Artificial Intelligence, Conservative Dentistry, Machine Learning.*

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I. Introduction

Conservative dentistry and endodontics emphasize the preservation of natural tooth structure by focusing on the prevention, early diagnosis, and treatment of dental caries, pulpal diseases, and periapical pathologies. (1) The rapid advancement of AI has been largely driven by technologies such as deep learning and natural language processing (NLP). Deep learning models can recognize intricate patterns within large and complex datasets, while NLP enables machines to comprehend, interpret, and produce human language effectively. (2)

The field of artificial intelligence traces its origins to the Dartmouth Conference held in 1956, where computer scientist John McCarthy introduced the term "artificial intelligence." The conference is widely regarded as the foundation of AI research, as it focused on exploring the potential for designing machines capable of replicating human intellectual abilities. (3)

Early research in artificial intelligence primarily focused on developing algorithms to solve mathematical and logical problems using symbolic reasoning techniques that emulated human problem-solving processes. During the late 1980s and 1990s, the focus gradually shifted toward neural networks and machine learning, with researchers investigating interconnected artificial neurons inspired by the structure and function of the human brain. The availability of large datasets and increased computing power during the 2000s led to the emergence of deep learning, enabling AI systems to recognize complex patterns from unstructured data. More recently, reinforcement learning has further advanced AI by allowing systems to learn through interaction with their environment, with applications in robotics, gaming, and optimization.(4) Artificial intelligence has become an important tool in dentistry, transforming multiple areas of oral healthcare through data analysis and machine learning techniques. By processing large datasets, AI systems can identify patterns and make accurate predictions, thereby supporting diagnosis, treatment planning, patient care, and practice management. (5) In particular, AI enhances diagnostic accuracy by analyzing radiographs, images, and patient records to detect oral diseases. Continuous learning from large datasets further improves its performance, enabling earlier detection of conditions and contributing to improved clinical outcomes. (5)

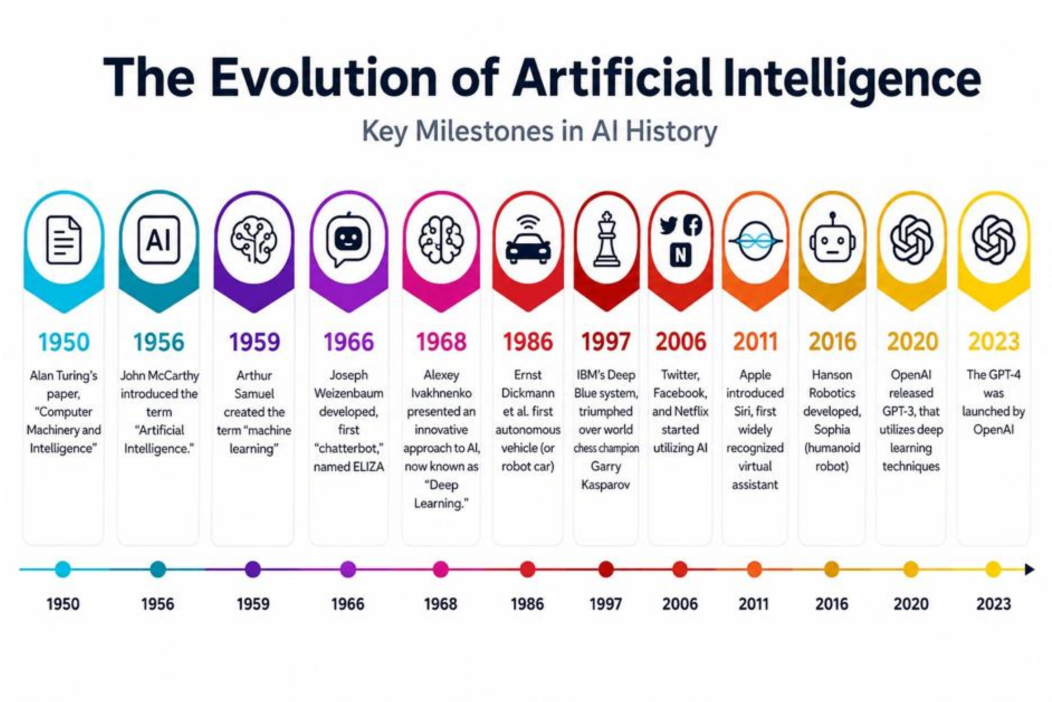
AI and ML can also be applied to personalized treatment planning, using predictive models to estimate the likelihood of caries progression or endodontic complications based on patient specific characteristics. (6) Despite these advancements, issues related to data quality, ethical considerations, and the requirement for rigorous validation continue to limit the widespread adoption of these technologies. [6] Studies highlight the importance of interdisciplinary cooperation between dentists and data scientists in creating dependable AI systems tailored to clinical practice. [7] The aim of this narrative review was to investigate the conceptual foundations, evolution, and practical uses of AI and ML and its future developments in conservative dentistry and endodontics, with particular attention to their types, approaches, advantages, and constraints.

Artificial intelligence (AI)

Artificial Intelligence (AI) is the field of developing computer systems that can perform tasks normally associated with human intelligence, including reasoning, problem-solving, decision making, learning, and understanding information. [8] Artificial Intelligence (AI) comprises several specialized subfields, including machine learning (ML), natural language processing (NLP), and computer vision, each playing a vital role in enabling intelligent system capabilities. In Conservative Dentistry and Endodontics, these technologies improve diagnostic accuracy, streamline clinical procedures, and support more efficient treatment planning.[9]

History of Artificial intelligence

The integration of Artificial Intelligence into healthcare began in the 1960s, with the emergence of expert systems. One of the earliest examples was **INTERNIST-I**, developed in the 1970s, which assisted clinicians by generating comprehensive differential diagnoses in internal medicine.[10] Initially, AI systems relied on predefined rule-based algorithms, restricting their capacity to address uncertainty and variability in clinical data. The introduction of machine learning in the 2000s marked a significant milestone by enabling data-driven analysis of extensive datasets, exemplified by the application of support vector machines for cancer classification. [11] The adoption of AI in dentistry accelerated during the 2010s, supported by research highlighting its capability to accurately identify periapical lesions. At present, AI systems in health sciences increasingly rely on deep learning techniques and big data analytics to strengthen diagnostic processes, refine treatment planning, and improve clinical outcomes. [12,13] Currently, AI applications in healthcare, including dentistry, utilize deep learning techniques and big data analytics to improve diagnostic accuracy, optimize treatment planning, and enhance patient outcomes.



Types of AI

Artificial Intelligence can be categorized according to its capabilities into three types: narrow AI, general AI, and superintelligent AI. Narrow AI, the most widely used form, is designed to perform specific tasks and has demonstrated remarkable effectiveness in applications such as detecting dental caries on radiographs, often achieving greater sensitivity than human experts. [14] General AI is intended to replicate human-level intelligence across diverse domains but has not yet been realized in practice. Superintelligence, a speculative future stage of AI, would surpass human cognitive capabilities and, although it could revolutionize healthcare, it also raises substantial ethical and safety concerns. [15]

Based on functional capabilities, AI is categorized into reactive machines, limited memory, theory of mind, and self-aware systems. Reactive AI responds exclusively to present stimuli and does not retain previous experiences, resulting in limited adaptability. Conversely, limited memory AI leverages historical data to enhance predictive performance and clinical decision making, as demonstrated by its application in endodontic working length determination. [(16)] Theory of mind AI, which is designed to recognize and interpret human emotions and intentions, and self-aware AI, which would possess consciousness and self-awareness, remain theoretical concepts. However, if realized, these advanced forms of AI could significantly enhance patient communication, personalized care, and clinical interactions in dental practice.

Application of AI in healthcare

In healthcare, AI applications can be broadly categorized into diagnostic, predictive, and operational systems. Diagnostic AI, which is extensively used in dentistry, analyzes radiographic images to accurately identify pathologies such as periapical lesions, thereby supporting early diagnosis and clinical decision-making. [(17)] At present, three major AI-based approaches have been developed for the identification of dental caries. These include AI driven image analysis for caries detection, AI-assisted caries risk assessment, and the integration of artificial intelligence with Computer-Aided Diagnosis (CAD) systems to improve diagnostic accuracy.

Predictive AI systems analyze patient data to estimate the risk of disease progression, including dental caries, with reported predictive accuracies as high as 97.1%, as demonstrated by Hung et al. [(17)] Furthermore, operational AI enhances healthcare delivery by streamlining administrative activities, such as appointment scheduling, thereby increasing the efficiency of clinical workflows.

Machine learning

ML is a subfield of AI that enables systems to learn from data and improve performance without explicit programming. ML algorithms identify patterns in datasets, making them suitable for tasks like predicting dental caries risk or classifying root canal morphologies. [(18,19)] In conservative dentistry, ML-based approaches utilize clinical and radiographic information to enhance diagnostic accuracy and facilitate clinical decision-making. Herbst et al. demonstrated that convolutional neural networks (CNNs) could detect periapical lesions with an accuracy of approximately 89–90%, highlighting the potential of AI-assisted diagnostic systems in endodontic practice. [(19)] Machine learning (ML) systems are developed by training algorithms on annotated datasets, followed by validation using previously unseen data to assess their generalizability. This process typically includes feature extraction, model training, and performance evaluation using metrics such as sensitivity and specificity. In endodontics, ML has been applied to predict the outcomes of endodontic microsurgery [(20)] and to estimate the risk of root canal treatment failure. [(21)] Compared with conventional statistical approaches, machine learning is better equipped to capture complex non-linear patterns and analyze high-dimensional datasets, making it particularly advantageous for sophisticated dental applications. However, its effectiveness depends on the availability of comprehensive, high-quality training data and the selection of appropriate algorithms, highlighting the critical importance of developing standardized datasets for dental research and clinical AI applications.

Machine learning (ML) is broadly categorized into four types: supervised learning, unsupervised learning, semi-supervised learning, and representation learning. Supervised learning involves training algorithms using labeled datasets, where each input is associated with a known output. In dentistry, semi-supervised learning has been applied to classify dental caries on radiographic images, achieving improvements of approximately 6% and 3% in average pixel accuracy. [(22)] By learning the relationship between image features, such as pixel intensities, and diagnostic outcomes, supervised learning models are particularly well suited for diagnostic applications.

Unlike supervised learning, unsupervised learning analyzes unlabeled datasets to uncover underlying structures through clustering or dimensionality reduction techniques. In endodontic research, k-means clustering has been utilized to group root canal morphologies from CBCT images, facilitating the identification of anatomical variations relevant to clinical practice. [(23)] This approach is valuable for exploratory analysis but may lack interpretability without ground truth labels.

Semi-supervised learning uses both labeled and unlabeled data, addressing the limited availability of annotated dental datasets. In endodontics, it has been applied to detect periapical lesions by combining a small labeled dataset with a larger set of unlabeled CBCT images, improving model performance while maintaining scalability for clinical use. [(24)]

Representation learning automatically extracts relevant features from raw data, eliminating much of the need for manual feature engineering. In conservative dentistry, it has been successfully applied to identify tooth preparation margins by learning discriminative features from radiographic images.[(24)]

This approach strengthens model performance in complex tasks, such as tooth shade determination, by automatically capturing subtle image features that conventional methods may overlook. Overall, different ML techniques offer complementary advantages in dentistry, although their success depends on the availability of high-quality training data.

Deep learning

Deep learning, a branch of machine learning, uses multilayer neural networks to analyze complex datasets. In conservative dentistry and endodontics, it is widely applied to image based tasks, including the detection of dental caries and periapical lesions, through the automatic learning of hierarchical features from raw images.[24-29]

An artificial neural network (ANN) is a computational framework made up of interconnected neurons arranged into an input layer, hidden layers, and an output layer. Based on the number of hidden layers, ANNs are categorized as shallow neural networks or deep neural networks (DNNs), with the latter containing multiple hidden layers. [25]

DNNs utilize multiple hidden layers to learn complex patterns within high-dimensional data. In endodontics, they have been employed to detect periapical pathosis in CBCT images, achieving an accuracy of 92.8%.[25] DNNs are highly effective in extracting hierarchical features for complex tasks, such as identifying root canal morphology. However, they require large datasets and significant computational resources, while their "black-box" nature limits the transparency of their decision-making, which may hinder clinical acceptance. [26]

CNNs are a type of deep neural network optimized for image processing. They use convolutional layers to extract features such as edges and textures and pooling layers to reduce image dimensions while preserving essential information, making them well suited for dental imaging applications.[26] In conservative dentistry, CNNs are widely employed for diagnostic image analysis, including caries detection (82% accuracy) [27], classification of C-shaped canal anatomy from CBCT images, detection of vertical root fractures on panoramic radiographs (93% precision) [28], and identification of periapical lesions with 95% accuracy.[29,30]

Although CNNs have demonstrated excellent diagnostic performance, their success relies on large annotated datasets, which are often difficult to obtain in dentistry because of privacy concerns and imaging costs. They also require significant computational resources and have limited interpretability. Nevertheless, CNNs remain powerful tools for improving diagnosis and treatment, with ongoing efforts to enhance their transparency and generalizability.[29]

Recurrent Neural Networks (RNNs) are designed to analyze sequential data by maintaining information from previous inputs through recurrent connections. This enables them to capture temporal patterns, making them ideal for processing time-dependent or sequential data. [29]

In conservative dentistry and endodontics, RNNs are used to analyze time-series data, including patient treatment histories and sequential radiographic findings. By evaluating longitudinal clinical records, these models have demonstrated the ability to predict caries progression, with Hung et al. reporting an accuracy of 87% over a 12-month follow-up. [30]

Conventional RNNs are limited by the vanishing gradient problem, which impairs their ability to model long-term dependencies. LSTM networks address this issue by retaining important information over longer sequences, enhancing performance in dental applications. However, their use in dentistry is still limited by the scarcity of longitudinal datasets and the computational complexity of model training.[30]

Generative Adversarial Networks (GANs) consist of two neural networks trained together: a generator that produces synthetic data and a discriminator that evaluates its authenticity. This adversarial training process enables GANs to generate realistic and high-quality data.[30] Although GANs have significant potential, they are computationally intensive and prone to **mode collapse**, which limits the diversity of generated outputs. Their application in dentistry is promising, but further validation is needed to ensure the reliability of synthetic data in clinical diagnosis and treatment. [30]

Applications of AI in conservative dentistry and endodontics

Detection of Caries

Al-Khalifa et al. reviewed the use of AI for dental caries detection and found that CNN-based models have been extensively employed, achieving high diagnostic accuracy. [18] AI models still encounter difficulties in detecting caries in morphologically complex teeth, particularly molars. A CNN-based investigation demonstrated an accuracy of 91% for premolars and 89% for molars, highlighting the impact of anatomical complexity on diagnostic performance. [31] Machine learning (ML) and deep learning (DL) have emerged as powerful techniques for the diagnosis of dental caries and the prediction of caries risk. These methods have demonstrated considerable potential in improving diagnostic accuracy and supporting clinical decision making. Nevertheless, their effectiveness is highly dependent on the availability of large, high-quality, and comprehensively annotated datasets, which are essential for training, validating, and generalizing robust predictive models. [22] AI-driven automation of caries detection improves diagnostic consistency and treatment planning in conservative dentistry. However, its accuracy depends largely on the quality of the training data and the resolution of the radiographic images.

Identification of Tooth Preparation Margins

AI-based approaches have significantly improved the identification of tooth preparation margins in restorative dentistry by enabling automated analysis of intraoral scans and radiographic images. Representation learning algorithms effectively extract discriminative features, including preparation margin contours, and have demonstrated a margin detection accuracy of approximately 89%, highlighting their potential to enhance the accuracy and efficiency of restorative procedures. [(32)] Artificial intelligence has been increasingly applied to the assessment of restoration margins by automatically identifying defects such as secondary caries and marginal gaps that may compromise restoration integrity. Early detection of these defects enables timely clinical intervention, thereby improving the durability and longevity of restorative treatments. However, the diagnostic performance of AI systems may be affected by variations in restorative materials, imaging artifacts, and differences in image quality. Consequently, further research is required to develop robust and generalizable algorithms capable of maintaining high diagnostic accuracy across diverse clinical conditions. [(32)]

Tooth Shade Determination

Artificial intelligence has significantly improved tooth shade determination by automating the analysis of intraoral images and matching the detected tooth color with standardized shade references, such as the **VITA Shade Guide**. This approach reduces subjectivity and enhances the consistency of shade selection during restorative procedures. Shetty et al. conducted a systematic review to evaluate the accuracy of AI-based systems in dental shade selection and concluded that these technologies demonstrate considerable potential for improving the precision and reproducibility of color matching in clinical practice. [(33)] The systematic review evaluated 53 studies and reported the use of multiple AI algorithms for dental shade matching, including CNNs, ANNs, SVMs, fuzzy logic, random forests, decision trees, and KNN-based methods. Decision tree regression achieved the highest accuracy (99.7%) for predicting shades of leucite-based dental ceramics, followed by fuzzy logic (99.62%) and SVM with cross-validation (97%). [(33)]

Detection of Root Canal Morphology

Artificial intelligence, particularly Convolutional Neural Networks (CNNs), has shown considerable potential in the assessment of root canal morphology by analyzing CBCT images to identify and classify canal configurations. CNN-based models have achieved a reported diagnostic accuracy of 86.9%, demonstrating their effectiveness in supporting endodontic diagnosis. [(34)] Nevertheless, the translation of this technology into routine clinical practice remains challenging due to factors such as limited availability of large annotated datasets, variability in CBCT image quality, computational requirements, and concerns regarding the interpretability and generalizability of AI models. In addition, the performance and reliability of AI models are highly dependent on the quality of the input images. Images should possess adequate resolution and dimensions, clearly focus on the region of interest, and include sufficient surrounding anatomical context to ensure that all clinically relevant information is available for accurate analysis and diagnosis. [(35)] These models segment root canal anatomy, assisting treatment planning by detecting anatomical variations, including accessory canals.[(27)] By enabling precise assessment of root canal anatomy, this application minimizes procedural errors during endodontic treatment and contributes to improved treatment outcomes. Nevertheless, its performance relies heavily on high-quality imaging and extensive training datasets, the availability of which remains a significant limitation.

Detection of Periapical Lesions

Artificial intelligence (AI) has substantially improved the detection of periapical lesions, an essential component of endodontic diagnosis. Convolutional Neural Networks (CNNs) and other deep learning models analyze panoramic radiographs and cone beam computed tomography (CBCT) images to accurately identify periapical radiolucencies, with reported sensitivity rates of up to **92.5%**. [(12)] A study conducted by Orhan et al. reported that artificial intelligence models were capable of differentiating periapical lesions from other radiolucent lesions, including cysts, with a specificity of **90%**, highlighting their diagnostic potential. [(24)] AI systems aid in the early diagnosis of periapical lesions, enabling timely treatment and reducing the risk of complications such as bone loss. They also assess lesion size and monitor disease progression to support treatment evaluation. Calazans et al. reported that CNNs achieved **68–70%** accuracy in classifying periapical lesions. [(36)] Despite its promising performance, AI faces several challenges in the diagnosis of periapical lesions, particularly in differentiating healing lesions from persistent pathology. In addition, the lack of standardized imaging protocols may affect the consistency and reliability of AI-based analyses.

Nevertheless, the high diagnostic accuracy of AI makes it a valuable adjunct in endodontics, with the potential to improve patient outcomes through precise, objective, and consistent lesion detection.

Determination of Vertical Root Fracture

Fukuda et al. investigated the application of Convolutional Neural Networks (CNNs) for the detection of vertical root fractures using panoramic radiographs. Their findings suggested that

CNN-based models represent a valuable diagnostic aid, with the potential to improve the accuracy and efficiency of fracture detection while supporting clinical decision-making in endodontics. [28] AI-based models are capable of detecting fracture lines that may not be visible on conventional radiographs, supporting earlier diagnosis and more effective treatment planning. This capability improves prognostic assessment in endodontics. Nevertheless, model performance is constrained by the quality and resolution of imaging data, as well as the limited availability of large annotated datasets for training. [29]

Working Length Determination and Detection of Apical Foramen

Artificial intelligence has been increasingly utilized in endodontics to improve the determination of working length and the detection of the minor apical foramen through the analysis of radiographic images. Accurate working length measurement is essential for the success of root canal treatment, and AI-based methods have shown considerable promise in enhancing this process. Saghiri et al. demonstrated that Artificial Neural Networks (ANNs) can function as an adjunctive tool for identifying the radiographic apical foramen, thereby increasing the precision and reliability of working length measurements and supporting more accurate endodontic treatment. [37] A subsequent investigation by Saghiri et al., published in the same year, assessed the accuracy of ANN based working length determination using a human cadaver model that closely replicated the clinical environment. [38] The investigators reported no statistically significant discrepancy between the root length measurements generated by the ANN and the true measurements obtained after tooth extraction. Additionally, the ANN demonstrated superior performance in detecting the minor apical constriction on IOPA radiographs, achieving an accuracy of **96%**, compared with **76%** for the endodontist. [37] ANNs appear to provide more accurate working length measurements than endodontists when using IOPA radiographs. This improves the precision and success of root canal treatment, although its performance depends on high-quality images and standardized imaging protocols.

Challenges in the use of AI in conservative dentistry and endodontics

Despite its considerable potential, the widespread adoption of artificial intelligence (AI) in dentistry is hindered by several significant challenges. One of the primary limitations is the limited availability of large, high-quality, well-annotated datasets. Dental imaging datasets are often restricted because of patient privacy concerns and the high costs associated with image acquisition and annotation, which can reduce the ability of AI models to generalize effectively across diverse patient populations. [2] The "black box" characteristic of deep learning models, including CNNs, limits their interpretability, making it difficult for clinicians to understand and trust AI-based diagnostic decisions [15] The substantial computational resources and financial investment required for AI implementation restrict its widespread adoption, especially in low-resource environments. Furthermore, ethical issues, including data security, patient privacy, and the risk of excessive reliance on AI systems, may adversely affect independent clinical decision-making. [15] AI models may demonstrate reduced performance when encountering uncommon or anatomically complex cases, such as unusual root canal morphologies, owing to their limited representation in training data. This underrepresentation can lead to diagnostic errors and reduced model reliability. Addressing these challenges necessitates standardized datasets, explainable AI algorithms, and collaborative efforts among clinicians, researchers, and data scientists to facilitate the safe integration of AI into clinical practice. [3]

Future directions in AI conservative dentistry and endodontics

Artificial intelligence in dentistry continues to evolve at a rapid pace, with ongoing advancements in computational algorithms and their clinical applications. These developments have the potential to improve diagnostic precision, facilitate personalized treatment planning, and enhance the quality of patient care. The major areas of future development include the following. [39]

Predictive analytics: AI algorithms can leverage large datasets to predict disease progression, treatment outcomes, and patient-specific risks. By analyzing historical patient data, genetic information, lifestyle factors, and treatment records, AI can help dentists make more informed decisions and develop personalized treatment plans.

Natural language processing: AI systems can be trained to understand and process dental specific terminology, patient medical histories, and clinical notes. This would enable them to extract valuable insights from unstructured data and facilitate seamless integration with electronic health records systems[39]

Virtual assistants: AI-powered virtual assistants can assist dental professionals in various tasks, such as appointment scheduling, patient communication, and data management. These assistants can be designed to provide evidence-based recommendations, answer patient queries, and streamline administrative workflows, freeing up more time for dentists to focus on patient care. [39]

Robotics and automation in dentistry involve the integration of AI with robotic systems to carry out highly precise and automated clinical procedures. Such robotic technologies can assist in tasks like tooth preparation, dental implant placement, and other repetitive procedures, ensuring greater accuracy, minimizing human error, and improving overall treatment outcomes. (40)

II. Conclusion

AI and ML have transformed conservative dentistry and endodontics by improving diagnosis, treatment planning, and procedural accuracy. They help detect caries, analyze root canal anatomy, and estimate working lengths with high precision, while also enabling personalized treatment and better clinical efficiency.

However, challenges such as limited datasets, high computational demands, lack of transparency, and ethical concerns (like data privacy and over-reliance on AI) limit widespread use.

Addressing these issues through better data standardization, improved interpretability, and collaboration between clinicians and technologists can help integrate AI more effectively into routine dental practice.

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