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Review Article

Transforming Shade Selection in Dentistry: A Review on Artificial Intelligence-Fuzzy Logic and Convolutional Neural Networks

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Abstract

AI has been a significant force in healthcare for quite some time, and its impact in dentistry is increasingly evident. It can address clinical challenges and enhance the efficiency of practitioners. Lighting conditions, color space models, shade matching devices, and the type of AI algorithm affect the accuracy of the prediction of dental shades for restorative procedures. Various neural networks and knowledge-based systems have shown increased accuracy in predicting dental shades. AI models, including neural networks, CNNs, fuzzy logic, GANs, RNNs, and random forests, are utilised in these processes. The review highlights the use of AI, fuzzy logic, and CNNs in shade matching in restorative procedures in dentistry. Rapid AI advancements support tooth shade selection, disease classification, bone loss evaluation, severity grading, image analysis, and early detection of problems. Over the last decade, AI-driven innovations have generated increased global research interest. Like other medical fields, dentistry is increasingly adopting AI, driven by the growing amount of patient data that requires more innovative software for organization and analysis. AI offers benefits throughout the entire patient journey, from initial department visits to treatment completion and follow-ups, aiding dental and medical professionals. While AI is unlikely to replace dentists in the near future, learning how to incorporate it into future workflow effectively is crucial for enhancing patient care.

Artificial intelligence (AI), a subset of computer science, is widely utilised in various industries; however, its application in dentistry remains relatively limited. Most research focuses on automating dental image analysis, predicting diseases, forecasting treatment outcomes, and enhancing technologies such as 3D printing, shade matching, and electronic apex locators. This overview explains key AI concepts, explores potential applications of fuzzy logic and convolutional neural networks (CNNs) in shade matching in restorative dentistry, and discusses the challenges and limitations of incorporating AI into dental practices.

Keywords: Artificial Intelligence; Fuzzy Logic; Convolutional Neural Networks; Dental Shade Selection

Introduction

Artificial intelligence (AI) involves machines simulating human intelligence, encompassing areas such as machine learning (ML), natural language processing (NLP), computer vision, and robotics. Each domain has unique applications and algorithms, resulting in diverse outcomes [1]. With proper training, AI can surpass humans in accuracy and efficiency. In healthcare, AI's history dates back to the 1950s, starting with systems like Jack Whitehead's 'MIT Programmed Autoanalyser' by Technicon Corporation, used for analysing blood and urine samples. The 1970s witnessed the development of MYCIN, an expert system designed to diagnose infectious diseases. The 1980s brought advancements in ML algorithms, enhancing medical imaging and drug discovery, leading to systems like 'Intellicare' for mental health and 'CardioCom' for heart disease diagnosis in the 2000s [2].

The increasing availability of digital dental data has sparked growing interest in data-driven AI in dentistry, driven by its potential to improve diagnosis, expedite treatment outcomes, and enhance patient care. Recent studies have featured bibliometric analyses in fields such as orthodontics and maxillofacial radiology. Nevertheless, there appears to be no comprehensive bibliometric review that covers AI applications across the entire dental sector [3]. 'Going to the dentist is nothing to smile about. Dentistry is a stunningly inexact science' [4].

As AI continues to advance quickly, machine learning (ML) remains a powerful tool for managing complex data relationships. For instance, convolutional neural networks (CNNs) are utilised in image recognition to detect nonlinear features, achieving high accuracy in tasks such as measuring facial landmarks, identifying implants, and spotting dental caries. In colour analysis, ML techniques like support vector machines (SVM) and decision trees (DT) are employed to classify tooth colours [5].

Deep learning, a form of ML using multiple neural layers, also called convolutional neural networks (CNNs), is widely used to analyse complex dental images and identify patterns automatically. Recent rapid progress in deep learning continues to boost AI's societal influence [6]. In healthcare, AI enhances patient care by facilitating accurate diagnoses and reducing errors. In dentistry, AI offers numerous benefits, resulting in improved health outcomes. Deep learning employs multilayered neural networks that learn hierarchical features by passing data (such as images) and labels (like a carious tooth or lesion location) through the network, adjusting model weights for improved accuracy [7]. CNN's based on deep learning have achieved high accuracy in detecting dental caries on periapical radiographs and identified impacted supernumerary teeth in patients with fully erupted maxillary incisors on panoramic radiographs. The advanced Mask R-CNN model has performed well in automatic tooth segmentation and apical lesion detection [8].

Recent studies show that artificial neural networks (ANNs) can serve as a second opinion for locating the apical foramen on radiographs and enhance the accuracy of working length measurements. Additionally, ANNs have been used to determine the shade, light-curing unit, and Vickers hardness ratio of bottom-to-top composites in laboratory tests [9].

Recent research highlights AI's extensive applications in dentistry, including the detection of abnormalities and cancers via radiographs and histopathology, the design of implants and crowns, the determination of tooth preparation boundaries, the analysis of growth trends, the estimation of biological age, the prediction of pulp stem cell viability, the exploration of gene expression in periapical lesions, forensic dentistry, and the prediction of treatment results. Nevertheless, three primary challenges persist: usability, return on investment (ROI), and proven effectiveness, all of which need thorough evaluation [10].

Artificial intelligence in dentistry

Artificial intelligence (AI) is extensively applied in dentistry, especially for diagnosis and decision-making. In healthcare, AI is categorised into two main areas: virtual, encompassing electronic health records, diagnostic systems, and treatment planning software; and physical, involving robot-assisted surgeries, intelligent prostheses, and related technologies [7]. Currently, AI is revolutionising dental aesthetics by enabling precise shade matching through devices like spectrophotometers and image analysis software, offering objective colour evaluations aligned with digital shade guides. Smartphone applications utilise AI to suggest shades from photos and integrate with CAD/CAM systems to ensure prosthetics accurately match patients' teeth [11]. AI improves dental professionals' efficiency and enriches patient experiences with virtual try-ons and customised material suggestions. Its learning ability enhances accuracy over time, and cloud platforms facilitate collaboration between practices and laboratories for better restorations. Additionally, AI supports dental education by providing analytical tools for skill development and clearer visualisations of expected outcomes, improving communication with patients [12]. It also enables remote consultations with adaptive algorithms that address lighting challenges. The integration of AI into dental practice aims to enhance the quality of care and patient satisfaction; however, its novelty requires rigorous research to verify its effectiveness. Ongoing studies and trials are essential for establishing a robust evidence base for AI's role in dental shade matching. Methods such as artificial neural networks (ANN), convolutional neural networks (CNN), and fuzzy logic demonstrate promising potential in detecting and diagnosing oral lesions that are often overlooked by the human eye [13].

AI analyses dental images for caries, apical lesions, and periodontal bone loss, supports landmark detection in orthodontics, and assists with anatomical segmentation. It is also involved in dental robotics and virtual reality (VR) applications for educational and therapeutic purposes. AI promotes self-dentistry and tele dentistry, enabling patients to consult experts and perform routine check-ups remotely. Fundamental to most AI systems are machine learning (ML) and deep learning (DL) [14]. As AI advances rapidly, its influence on dentistry, particularly in digital protocols, is expected to grow significantly. Data collection through AI can improve patient care in three phases: pre- appointment (AI Patient Manager, AI Patient History Analyzer, AI Scientific Data Library), during the appointment (AI Problem Detector, AI Treatment Proposals, AI Instant Feedback), and post- appointment (AI Laboratory Work Designer, AI Patient Data Library, AI Clinical Evaluation) [15].

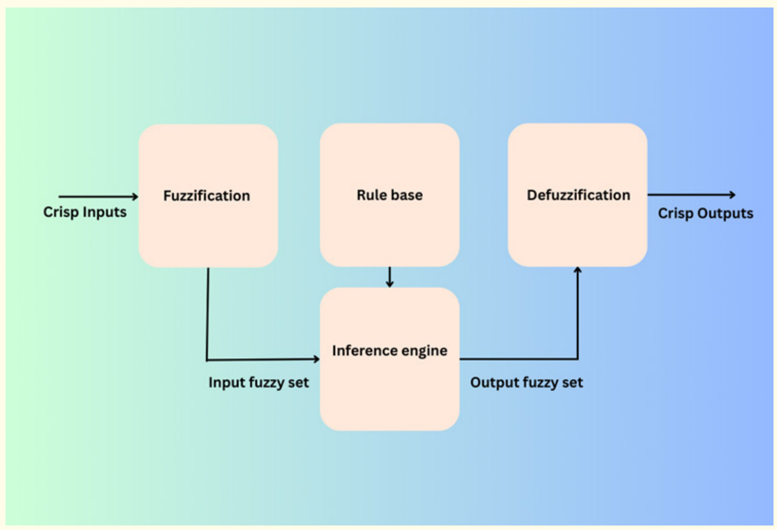

Diagram 1: A flowchart diagram illustrating the components of Fuzzy Logic System.

Fundamentals of shade matching in dentistry

Shade matching in dentistry is challenging because current shade guides lack a standardised framework, leading to inconsistencies caused by batch production variations. Clinicians often perceive colours differently, which can complicate communication, as technicians typically do not see the patient and rely on written prescriptions based on shade guides, such as Vita Lumin A3 [17]. Clear communication between dentists and technicians is essential for better outcomes. Advances in photography and computing have popularised digital cameras for colour imaging, capturing data to create images for online sharing and display. Specialised software can analyse these images to determine colour values in specific areas or throughout the entire image, offering a cost-effective alternative to traditional tools such as spectrophotometers or colourimeters [18]. The CIELAB system was developed to provide a uniform colour space. As patient expectations for natural-looking indirect anterior restorations increase, accurate shade matching becomes even more critical, especially as patients become more aware of their teeth's role in overall aesthetics. Despite widespread use of shade guides and intraoral digital photos, the process remains subjective and inconsistent, with colour mismatches affecting up to 63% of ceramic restorations [19]. Factors like rapid dehydration, lighting conditions, operator experience, and individual visual genetics complicate shade selection. To address human vision limitations, devices such as spectrophotometers and colourimeters are recommended, though they are more expensive and require training. These tools offer more objective results. Cost-effective options include the OptishadStyleItaliano colourimeter, the OptiShade iOS app, and Matisse software, which provide reliable readings without relying solely on traditional shade guides or DSLR cameras [19].

Selecting the right prosthetic tooth shade is also challenging due to metamerism, a phenomenon where colours appear different under various lighting conditions. Both laboratory and clinical lighting influence the perceived shade. Although natural and prosthetic teeth can appear similar over time, factors such as eye fatigue and external conditions can alter perception, leading to incorrect shade choices and suboptimal aesthetic outcomes [20]. Clinicians can improve their view of teeth by carefully optimising lighting conditions. When assessing shape, surface texture, value, translucency, hue, and chroma, using more effective techniques is crucial. Begin by re-examining the chromatic elements- value, hue, and chroma, with a fresh perspective. Remember that brightness (value) depends on both the tooth's chroma and the surface's reflectivity. Utilising a value guide in low light can help achieve a more accurate evaluation of chromatic features [21].

Fuzzy logic in dental shade matching

Deep learning plays a key role in machine learning, while 'fuzzy' refers to concepts that are vague or imprecise. Deciding if a statement is true or false in daily life can be difficult. Fuzzy logic provides useful reasoning tools for managing this uncertainty. Developed by Lotfi Zadeh, it gives a transparent and flexible approach to machine learning. A typical fuzzy logic system includes four main parts: 1) Rule Base, 2) Fuzzification, 3) Inference Engine, and 4) Defuzzification. Its main goal is to mimic human reasoning, which often involves vague ideas [22]. A fuzzy logic-based expert system was developed to interpret ambiguous data on dental signs and symptoms associated with mobile teeth, thereby supporting informed dental decisions [23]. Dental and oral health issues are common across all ages, but many patients avoid treatment due to fear or costs. Ambara and colleagues developed a quick, low-cost fuzzy system that enables consultations without specialised equipment, helping reduce patient anxiety. Herrera and his team used a fuzzy system to predict tooth colour changes after bleaching, based on initial chrome measurements, and matched shades with the Vita shade guide [24].

Typically, fuzzy systems involve steps such as fuzzification, which converts numeric data into fuzzy sets using membership functions; a knowledge database with linguistic categories and rules; the inference engine, which processes data and regulations to mimic human decision-making; and a final step where rule outputs are combined into a single value, either numeric or categorical [25]. Since their development, fuzzy systems have been widely studied and remain important in the field of intelligent computing. Their main advantage is interpretability rather than accuracy. Recent developments include genetic fuzzy systems and automatic optimisation techniques that enhance performance on specific datasets, along with type-2 fuzzy systems that better handle data uncertainty [26]. Colour matching is the most common method for assessing dental shades. Most dental materials utilise the VITA system for shade identification; however, challenges include subjectivity and variation in shades among manufacturers. Early methods employed fuzzy set-based colour naming within the CIELAB colour space to define a dental colour space based on VITA shades. Psychophysical studies linked colour measurements of dental materials from different brands with VITA shades using fuzzy sets that incorporated subjective perception data. Clinical effectiveness was confirmed through colourimetric measurements of composite resin samples from two manufacturers [17]. Compared to traditional shade guides, fuzzy technology offers significant improvements. Its role in biomimetic colour analysis and modelling is substantial and likely to grow. Fuzzy logic systems, such as FL and TSK, show promise for simulating human colour perception, particularly in determining colour difference thresholds in dentistry. Their ability to model complex relationships yields better performance than earlier S-shaped models in evaluating colour differences and visual thresholds in tooth shade [27].

Color details are essential for precise color matching. Hue and saturation hold a crucial place in shade selection in restorative dentistry. A study was conducted that used the HSV color model for dental shade matching, recording results with metrics like PSNR, SSIM, CPSNR, and S-CIELAB. To enhance accuracy, images were multiplied by machine learning-derived coefficients, raising PSNR from 97.64% to 99.93%. The fuzzy decision model achieved 99.78% accuracy, overpowering previous methods. This study is the first to include HSV, PSNR(H), PSNR(S), and SSIM in dental color matching, outweighing earlier techniques [28].

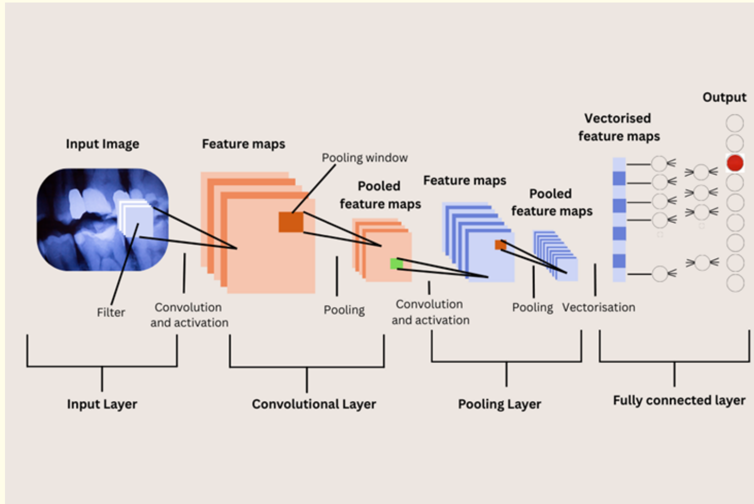

Diagram 2: A diagram illustrating Convolutional Neural Network (CNN) architecture, showing the progression from an input image through various layers to an output [2].

Convolutional neural networks (CNNs) in shade selection

A Convolutional Neural Network, also known as a ConvNet, is a specialised type of deep learning primarily designed for tasks such as object recognition, including image classification, detection, and segmentation. Convolutional neural networks (CNNs) operate on grid-structured data using multiple layers. They analyse images, extract relevant features, and differentiate between images in deep learning. Training CNNs is usually easier than other image classification techniques, as they can learn filters automatically. Spatial pattern-detecting data filters make CNNs very effective for visual applications [29].

Deep learning involves continuously processing images and labels, for instance, detecting rotten teeth or lesions, through neural networks that progressively refine results to maximise precision. CNN-based models have been able to identify dental caries in periapical radiographs and impacted supernumerary teeth in patients with fully erupted maxillary permanent incisors using panoramic radiographs. After being thoroughly trained, the Mask R-CNN is capable of automatically segmenting teeth in scenic images and can be applied to identify apical lesions [30]. Additionally, a robotic system can assist with routine dental procedures, providing precise, safe, and accurate 3D guidance during tooth preparation. AI-based CNNs can distinguish between dental arches, aid in designing removable partial dentures, and analyse how facial attractiveness and perceived age are affected by orthognathic treatments, providing objective and reproducible scores. By merging facial and intraoral photographs of the maxillary anterior teeth, dentists can study the shape and position of the maxillary anterior teeth. Deep learning models, or CNNs, extract features from stacked filters and are primarily used to handle extensive and complex images [2].

The creation of self-improving back-propagation algorithms, which improve incrementally, and increased computational power, accelerate deep learning. Due to these developments, AI, specifically deep learning, can be applied in various real-world scenarios across multiple areas [31]. In medicine, the diagnostic performance of deep learning methods is approaching that of human experts, transforming computer-aided diagnosis from a ‘second-opinion’ device into a more supplementary role. AI applications in dentistry are also progressing at a fast pace. Most pre-trained networks, such as AlexNet, VGG, GoogLeNet, and Inception v3, have been shown to provide good results in studies. Still, CNN architectures always prefer to transform from shallow to deep networks. Networks can be deep or problem-specific, homemade, or composite networks [15].

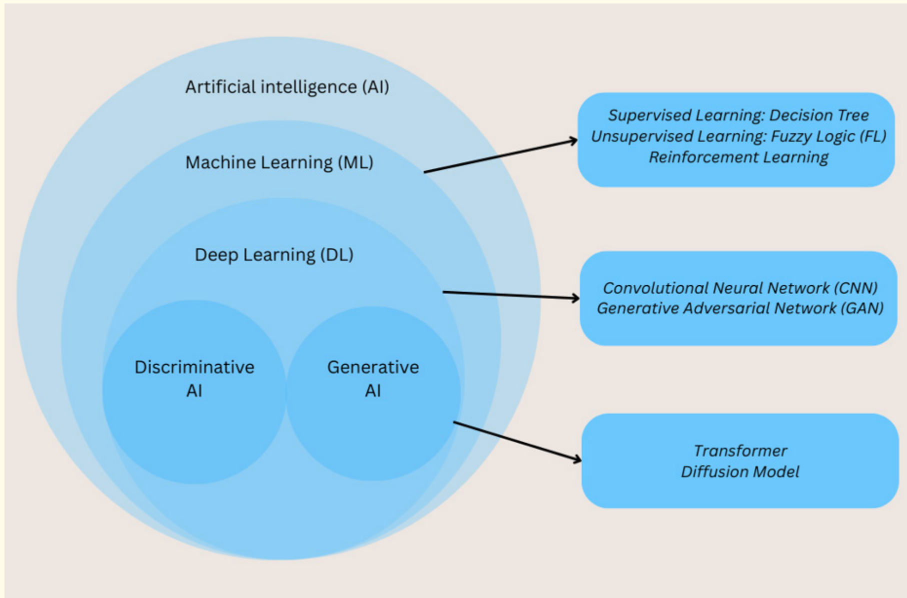

Diagram 3: A Venn diagram showing the categorisation of Artificial Intelligence [16].

Clinical implementation and practical considerations

The dental AI market involves integrating artificial intelligence into dentistry to enhance diagnosis, treatment planning, and patient care through tools such as image analysis, diagnostic systems, and treatment software. Driven by the increasing adoption of digital technology, the rising demand for accurate diagnostics, and efforts to enhance patient outcomes, this market is experiencing rapid growth. It is expected to reach $ 3 billion by 2028, with a compound annual growth rate (CAGR) of 27% from 2023 to 2028. CAGR measures growth over time by comparing the initial and final values, raised to the power of 1 divided by the number of years [2]. Key segments include diagnosis, treatment planning, and patient management, with diagnosis anticipated to hold the most considerable share and treatment planning experiencing the fastest growth. The primary users are dental clinics, educational institutions, and research centres, with dental clinics leading the market. Geographically, North America is projected to dominate due to the presence of numerous AI companies and widespread technology adoption, followed by Europe, which also has many clinics and high technology adoption rates [32].

Various devices, such as spectrophotometers, colourimeters, and digital cameras, are used for objective colour matching. Intraoral spectrophotometers are regarded as highly accurate and reliable for matching natural tooth colour, measuring reflectance or transmittance at specific wavelengths. They analyse visible spectra, with results expressed in CIE L*, a*, b* values and converted into shade systems. Limitations include sensitivity to lighting conditions, device positioning, and tooth surface texture [33].

AI research in dentistry encompasses multiple specialities and is evaluated using metrics such as accuracy, sensitivity, specificity, F1 score, and AUC. Properly splitting data into training, testing, and validation sets is essential, along with a carefully designed study. Comparing efficiency using ROC curves is challenging, as most studies focus on limited aspects of the topic. The MICLAIM checklist was developed to promote usefulness and transparency when applying AI in healthcare [34]. A significant concern that is frequently raised, especially amid digitalisation and the widespread adoption of electronic health records, is patient privacy and confidentiality. As AI becomes more embedded in healthcare, the risks of data breaches or misuse of patient information increase, potentially harming patients and eroding trust in healthcare providers. There are also concerns regarding accountability and transparency in AI-driven decisions [35]. If an AI algorithm makes a mistake or produces an unexpected outcome, determining responsibility and addressing the issue can be difficult, which may undermine patient confidence. Additional problems involve ensuring that AI supports rather than replaces clinicians, its role in training medical and dental students, and potential legal conflicts arising from the use of AI in healthcare. Another related concern pertains to geographical disparities. More developed nations have greater access to AI services as compared to underdeveloped ones [36].

Accuracy of AI in tooth shade selection

Like other AI systems, a set of test specimens with known colour coordinates and porcelain powder recipes was used to verify the accuracy of a CCM model. The colour differences between these specimens and the CCM predictions were calculated using colour difference formulas and compared to clinical visual thresholds to determine visibility [37]. One study found that the CCM system produced acceptable colour differences—below the threshold—when matching natural teeth and zirconia restorations. Furthermore, a BPNN-based CCM model outperformed visual matching in terms of shade accuracy, with the differences remaining below threshold levels. Another CCM model using SVM algorithms achieved 90% accuracy in tooth colour matching [38]. However, since few studies have examined AI's effectiveness in determining tooth shade, further research is needed. Colour information, especially hue (H) and saturation (S), is crucial for precise colour matching. A study introduced a dental shade matching method based on the HSV colour model, which was tested using metrics such as PSNR, SSIM, CPSNR, and S-CIELAB. These metrics measure lightness (L^*), green to red (a^*), and blue to yellow (b^*). Accuracy improved by applying machine learning-based weighted coefficients to dental images, reducing errors. The PSNR value increased from 64% to 93% using a fuzzy decision model. Results showed that this novel fuzzy decision method, combining HSV, PSNR (h), PSNR (s), and SSIM, applied here for the first time in tooth colour matching, achieved an overall accuracy of 78%, exceeding previous techniques. This method effectively combines HSV data with PSNR and SSIM, demonstrating enhanced performance [28].

Challenges and limitations

Nevertheless, the current literature has some limitations concerning AI in aesthetic dentistry studies. Several of the studies discussed in this article are inconclusive due to small sample sizes or the use of simulated environments, which may not accurately reflect actual practice settings. Additionally, the long-term success of smile designs suggested by AI and their impact on patients and clinical outcomes remain unknown because of the lack of multiple longitudinal studies. Similarly, ethical issues are still given insufficient attention, especially regarding the partiality of AI algorithms and their development process [11]. These limitations suggest that more comprehensive and realistic research is necessary to fully understand AI in aesthetic dentistry, including its strengths, weaknesses, opportunities, and potential threats. Some drawbacks of AI use in dentistry include the complexity of mechanisms and systems, high setup costs, the need for adequate training, and the tendency to use data for both training and testing, which can lead to data snooping bias [35]. Although AI models may appear to be futuristic and promising, their reliability with data from new patients is questionable. AI models require constant human monitoring as errors may occur. Being a machine, it lacks empathy towards patients. It can also be a reason for future unemployment. There are some issues regarding the quality of AI-generated questions, including unpredictability, ethical considerations, and a lack of creativity. Students may become overly reliant on AI and neglect to develop critical thinking and problem-solving skills [39].

The results of AI applications in dentistry are not yet broadly applicable. In conclusion, Artificial Intelligence is not a myth but our future industry. Its applications are steadily expanding across various fields. It cannot replace the role of a dentist, as dental practice involves not only diagnosing diseases but also correlating multiple clinical findings and providing treatment [40]. Nonetheless, a clear understanding of AI techniques and concepts will undoubtedly offer advantages in the future. We hope to see AI fully integrated into orthodontics, endodontics, and restorative dentistry (including reconstructive surgeries) soon. Currently, the main limitations are the availability of insufficient and inaccurate data. Therefore, it is the responsibility of dentists and clinicians to focus on collecting and inputting authentic data into their databases, which will soon be fully utilised for AI in dentistry [36].

Regarding ethics and AI research in dentistry, six principal principles emerge: prudence, privacy, responsibility, democratic participation, solidarity, and equity. It is noteworthy that most studies do not provide access to their data or the code developed, which limits the reproducibility of the research. Many studies are validated only internally, increasing the risk of bias. Furthermore, only a few addresses ethical considerations, suggesting that the medical community remains largely unaware of the moral issues surrounding AI research [41]. The next decade will reveal whether AI advancements produce practical, real-world applications or if a repeat of the AI winter dampens progress and enthusiasm. In healthcare, the stakes are particularly high. Concerns about data security, protection, and the capacity for computers to make critical medical decisions are valid. However, AI also offers the potential to revolutionise healthcare and dentistry by addressing common criticisms of traditional dental practices. Specifically, in dental research, the field must ensure that AI enhances dental care, reduces costs, and benefits patients, providers, and society as a whole [42].

Future Perspectives

AI applications in aesthetic dentistry are expected to continue expanding, driven by advancements in machine learning and digital technologies that improve diagnostic precision and personalise treatment and care planning. Future research may utilise more detailed patient information, such as genetic data and facial scans, to create customised smiles tailored to individual features [34]. Additionally, AI could be used to predict the long-term outcomes of aesthetic procedures and serve as a training resource for dentists, thereby enhancing its clinical value. Combining AI with traditional and expert methods seems to be the future path for aesthetic dentistry [9].

AI-powered wearables could monitor patients' oral health and prosthetic function in real-time, analysing factors like bite force and speech to recommend personalised prosthetic materials and designs. Overall, AI is expected to facilitate more individualised care, considering each patient's dental anatomy, habits, and history. AI-driven collaboration platforms will enable seamless communication among prosthodontists, lab technicians, and patients, allowing them to share data, treatment plans, and progress updates with ease and efficiency [43]. The inconsistency of AI performance in different populations and settings underscores the need for standardised benchmarks to evaluate and compare AI tools effectively. Such benchmarks would support the development of universally applicable AI systems and reduce performance disparities [44]. Future investigations should explore the combination of AI with emerging technologies, such as 3D printing, to transform restorative procedures and assess the long-term safety and effectiveness of AI-assisted treatments. Collaboration among researchers, clinicians, and policymakers is essential to address these challenges and promote responsible AI development in dentistry [16].

Conclusion

Studies have shown that AI models are reliable diagnostic tools for selecting tooth shades, but they are still being developed. More research is needed to confirm their effectiveness and accuracy. In one study, an intraoral scanner was found to match a spectrophotometer in shade selection using the VITA 3D-Master system; however, visual verification remains the most dependable method for achieving optimal clinical results. AI offers a promising solution to human limitations in shade matching, utilising advanced algorithms to achieve more consistent and objective results. Technologies such as machine learning models and neural networks can bypass human perceptual biases, operate independently of lighting conditions, and provide accurate colour measurements that extend beyond predefined colour spaces. These systems can analyse colour data precisely, ensuring clear communication between dentists and labs and enabling better-fitting dental prosthetics. AI's capacity to identify features and patterns provides a level of consistency and predictability that traditional methods lack, potentially improving clinical efficiency and patient outcomes in dental restorations. Recently, digital cameras and smartphones have been increasingly used to record tooth shades. These digital methods have been shown to produce accurate results comparable to those obtained through visual shade matching. However, no single method, digital or visual, is entirely reliable, repeatable, and precise on its own due to various factors that influence it. Different digital applications employ different shade analysis methods, making direct comparisons difficult. While many studies report accurate digital shade matching, the literature suggests that they should be used in conjunction with visual methods. Standardising digital techniques with cross-polarised filters, an 18% grey card, and ring lights at 5500–6000K temperature helps ensure consistent shade selection. Minor details in shade analysis can be easily communicated digitally to laboratory personnel, and data can be stored electronically for future reference.

In summary, AI's reliability in restorative dentistry is supported by its high diagnostic accuracy, precise treatment planning, and predictive analytics. Nevertheless, challenges such as the need for large, diverse datasets, ethical issues, and ongoing validation must be addressed. Collaboration among researchers and ongoing investigations into emerging AI techniques are essential to maximise AI's benefits in dentistry. Integrating AI advances into restorative dentistry offers significant improvements in diagnosis, treatment planning, and patient care. As technology progresses, AI-powered solutions are likely to lead to groundbreaking developments in precision-driven, patient-centred dental care (Bonny., *et al*. 2023). To advance AI research, studies should follow standardised ethical and methodological guidelines, particularly regarding data collection, transparency, privacy, and accountability. Creating a comprehensive framework for robust, reproducible, and clinically validated AI technologies will ease their integration into practice, ultimately benefiting both clinicians and patients by improving dental care.

AI is rapidly evolving in healthcare, but is still mainly in the research phase. Having more information can make research faster and provide better results. However, AI presents various risks, including privacy violations, ethical issues, and potential malpractice in medicine and dentistry. Its success in healthcare will require cooperation among developers, regulators, and stakeholders. Many questions remain unresolved, and a complete understanding of them is impossible to achieve. This uncertainty is why ongoing exploration is essential, rather than being a source of reluctance.

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