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Pixels, Precision, and Patient Care: The Rise of Digital Endodontics

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ABSTRACT: The integration of digital technologies is transforming endodontic diagnosis and treatment by improving efficiency, precision, and patient-centred outcomes. This review explores key innovations—including cone-beam computed tomography (CBCT), CAD/CAM systems, 3D printing, artificial intelligence (AI), and electronic health management systems (EHMS)—and their growing role in contemporary endodontic practice. CBCT enables high-resolution visualisation of complex root canal anatomy and periapical structures, supporting more accurate diagnosis and clinical decision-making. CAD/CAM technologies facilitate rapid chairside fabrication, enhancing workflow efficiency and patient satisfaction, while 3D printing allows the production of customised guides and anatomical models for improved surgical planning. AI-based tools and predictive analytics further assist diagnostic assessment and clinical judgement, and EHMS promote streamlined operations and interdisciplinary collaboration. Collectively, these advancements represent a shift towards more precise, personalised, and evidence-based endodontic care, underscoring the expanding role of digital technologies in shaping the future of the specialty.

KEYWORDS: Endodontics, Digital Dentistry, Cone-Beam Computed Tomography (CBCT), Computer-Aided Design/ Computer-Aided Manufacturing (CAD/CAM), 3D Printing, Artificial Intelligence, Machine Learning

I. INTRODUCTION

Endodontics, a clinical field focused on the management of the diseases of the pulp and periapical tissues, entails an advanced degree of precision. However, traditionally, treatment planning was established on manual techniques and conventional 2D X-rays, which would often miss the complexity and the diversity of the root canal system. Today, with the advent of digital technology, especially Cone Beam Computed Tomography (CBCT), endodontists can now obtain high-resolution 3D images, enhancing diagnostic accuracy and treatment precision.[1, 2] Furthermore, CAD-CAM technology has allowed the fabrication of high-precision restorations with reduced treatment duration.[3] Similarly, 3D printing has expanded the scope of endodontic microsurgery through the development of personalised surgical guides and anatomical models for better planning and intraoperative precision.[4,5] Artificial intelligence, through its various models like machine learning and deep learning, is transforming diagnostics, improving the detection rates, enabling reliable outcomes prediction and even better management through Electronic Health Records (EHRs).[6, 7]
This paper provides a broad analysis of these technological advancements with its impact on. contemporary endodontic practice.

II. Digital Imaging in Endodontics

Cone-Beam Computed Tomography (CBCT)

Cone-Beam Computed Tomography (CBCT) has greatly revolutionised diagnostic imaging by providing precise three-dimensional anatomical data of oral and maxillofacial structures, overcoming the drawbacks of conventional imaging such as image distortion, superimposition, etc. [8] Additionally, CBCT can provide thorough volumetric imaging, allowing for more accurate examination of periapical diseases and the root canal system.
The main clinical applications of CBCT are as follows:

- **Assessing the root canal anatomy:** A thorough three-dimensional representation of root canal systems, including complex anatomies like bifurcations, curvatures, isthmuses, and accessory canals, is provided by CBCT. The possibility of missing canals, a critical factor in

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endodontic failure, is greatly decreased by this accuracy.[9]Studies show that CBCT can identify more canals than periapical radiography and,conventional microscopy [10] improving treatment outcomes and lowering the need for retreatment.[8]

- **Identification of periapical conditions**: The high imaging resolution in CBCT makes it possible to thoroughly evaluate periapical lesions, such as granulomas, cysts, and apical periodontitis, which may go undetected on 2D radiographs because of anatomical noise of superimposition. [11] In a comparative research published in 2008, Low et al. found that CBCT could identify periapical pathology when periapical radiographs did not show any indications. Better treatment planning is made possible by its ability to distinguish between endodontic and non-endodontic lesions. Also it demonstrates how well the CBCT can visualise complex root canal anatomy and associated disease.[12]
- **Management of Endodontic Emergencies**: CBCT is an essential diagnostic tool for trauma-related complications, such as fractures, resorptive defects, and treatment-related complications, such as perforations, which are often missed by conventional imaging.[13,14] This enables more focused and informed emergency care. 4It is essential to the preoperative evaluation and treatment planning of surgical patients, such as retrograde fillings and apicoectomies.[15] Figure 1 illustrates the various applications of CBCT in the field of endodontics.

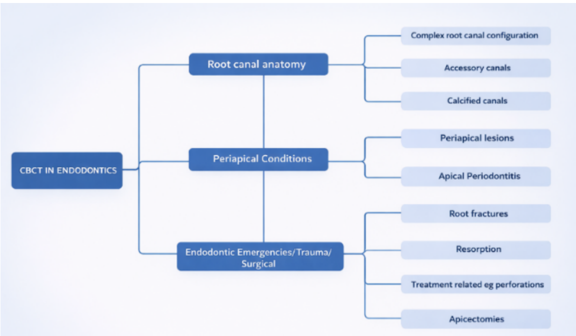

Figure 1: Applications of CBCT in the field of endodontics.

III. Computer-Aided Design and Manufacturing (CAD/CAM)

By enabling the creation of precise, customised restorations and significantly reducing treatment times, particularly during post-endodontic restorative procedures, CAD/CAM technology has dramatically improved clinical dentistry. Additionally, it has improved accuracy when making crowns, bridges, and inlays, enabling restorations that are tailored to each person's particular anatomical and functional requirements.[16]

Common Uses of CAD/CAM in Endodontics

- **Post-Endodontic Restorations**: Crowns and onlays, which are usually selected as the standard restorative solutions following endodontic therapy to offer durability and structural support, are now made with remarkable precision using CAD/CAM technology, guaranteeing an ideal fit while lowering the possibility of complications like fractures or recurrent decay.[4, 17]

- **Onlays and Endocrowns for Damaged Teeth:** For teeth that have experienced significant structural loss, CAD/CAM technology is used to create custom endocrowns and onlays that preserve the tooth structure while offering crucial support. [18]

- **Custom Posts for Internal Support:** When extra support is needed, CAD/CAM can create posts that are specifically designed to fit the tooth's shape and structure, particularly in teeth with complicated structures and multiple roots.[4, 19]

Workflow of CAD/CAM In Endodontic Restoration

The typical stages in the fabrication of CAD/CAM restorations are: [20]

1. **Digital Impression and Scanning**:
Following root canal therapy, an intraoral scanner takes a digital impression of the tooth. By eliminating the need for messy, conventional impressions, this improves patient comfort and accuracy.

2. **Restoration Design**:
Using specialised CAD software, the restoration is made to precisely replicate the contour of the tooth. During the design phase, occlusion, alignment, and aesthetics can all be improved.

3**. Milling and Manufacturing**: Using durable materials like ceramic or zirconia, a milling machine produces the restoration according on the computer design
.

4. **Fitting and Final Modifications**: The tooth is used to assess the finished restoration. Any necessary changes are made before the restoration is secured in place. Figure 2 shows the full process

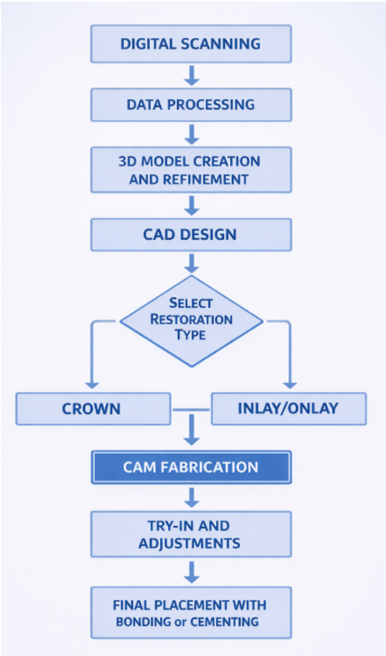

Figure 2: Illustration of the CAD/CAM workflow for endodontic restorations

IV. 3D-Printing

3D-Printed Surgical Guides in Endodontic Microsurgery:

It is only possible due to 3D printing that endodontic microsurgery now offers more options, especially for making personalised surgical guides. Digital imaging data, often from CBCT scans, is used to construct these guidelines.[21]

Applications of Custom 3D-Printed Tool in Endodontics

- **Tailored Access Guides**: When anatomical variations make root canal access difficult, 3D-printed aids help clinicians find precise entry spots, improving treatment accuracy.[22]
- **Surgical Guides for Endodontic Surgery:** These guides provide detailed instructions for angulation and depth during procedures like periapical surgeries, reducing the risk of complications.[23]
- **Temporary Restorative Solutions:** 3D printing enables the rapid fabrication of temporary restorations or occlusal guards, offering immediate solutions while permanent restorations are prepared. [24]

These applications demonstrate the versatility and practicality of 3D printing in modern endodontics.

Creation Process:

A digital model of the tooth and surrounding structures is created using CBCT scans. Once this model is imported into specialised software, the surgical guide is created depending on the particular requirements of the procedure. After completion, the guide is 3D printed, sterilised, and prepared for clinical usage.

Virtual Surgical Planning

Virtual surgical planning offers a thorough preview of intricate procedures by combining 3D images, CAD software, and occasionally augmented reality. This enables endodontists to model different surgical techniques and select the least invasive and most successful one.[25]

Key Steps in Virtual Planning:

1. **3D Data Reconstruction**: A highly detailed 3D model of the tooth, root structures, and surrounding bone is made using CBCT data.
2. **Identification of Key Landmarks**: To reduce risks during surgery, significant anatomical elements, such as blood arteries and nerves, are identified and marked.
3. **Surgical Simulation and Planning:** Physicians test access angles and design the most accurate course of action to reduce problems by using software to model the procedure.

The key steps in virtual planning have been illustrated in Figure 3

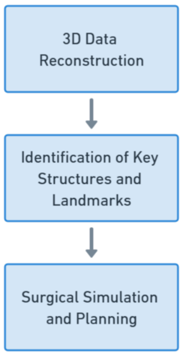

Figure 3: Key Steps in Virtual Planning

Reduced intraoperative time, increased accuracy, and greater safety are some advantages of virtual planning, particularly in complicated cases or retreatment situations where anatomy may change.

Digital Workflow for Endodontic Microsurgery

A simplified workflow that incorporates digital photography, planning, and 3D printing is made possible by the use of digital technologies. The computerised workflow frequently utilised in endodontic microsurgery is depicted in the flowchart below. (Fig. 4)

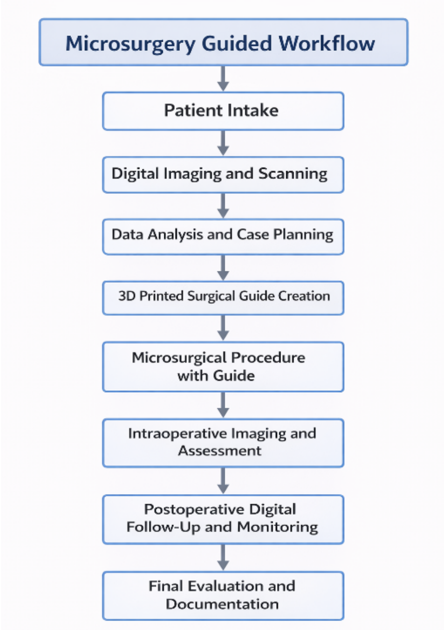

Figure 4: Digital Workflow in Endodontic Microsurgery

V. Artificial Intelligence and Machine Learning in Endodontics

By utilising enormous datasets and intricate algorithms, artificial intelligence (AI) and machine learning (ML) are transforming healthcare, including endodontics. These technologies improve outcome prediction, treatment planning, and diagnostic accuracy, enabling doctors to make better judgements.[26]

Applications of AI in Diagnostics and Imaging

AI is specifically adept at examining diagnostic images, comprising of the radiographs and CBCT scans. Major uses comprise:

• **Identification of Periapical Lesions and Root Fractures**: AI algorithms specifically the Convolutional Neural networks (CNNs) can detect the early periapical lesions and vertical root fracture from IOPARs and CBCT scans, that might be subtle or easily missed. Ekert et al. demonstrated a diagnostic accuracy of 92% in diagnosing Periapical lesions using a deep learning model, outperforming general dentists by a considerable margin.[27] Similarly, Setzer et al reported that AI algorithms could detect root fractures with higher constancy than humans, particularly in molars where there is limited visibility.[28]

• **Automated Measurement of Root Canal Sizes**: AI driven segmentation and measurement tools have been successfully used to automate root canal dimension assessments, resultin in the precise measurement of canal lengths and diametres, thereby reducing the interexaminer variability and increase the reproducibility of measurements as shown by Orhan et al, thus leading to more predictable treatment outcome and reducing the risk of over and under instrumentnation.[29]

• **Outcome Assessment After Treatment**: AI plays a crucial role in evaluating the healing by identifying residual infections, new lesions, or incomplete obturation fillings in follow-up visits, allowing for early intervention.[30]

Predictive Analytics in Endodontics

In order to anticipate treatment efficacy and detect risks, machine learning algorithms examine patient data, including imaging, medical history, and past results. Personalised, evidence-based care is encouraged by these concepts.[31]

• **Predicting Root Canal Treatment Success:** Machine learning algorithms have proven to be highly predictive in estimating treatment outcomes by assessing complicated multivariate data sets such as pulp vitality, canal shape, degree of curvature, and previous treatments. Using regression analysis and machine learning models, **Karobari et al. (2025)** evaluated the role of **root canal anatomical complexity** in predicting root canal treatment outcomes using regression analysis and machine-learning models.

Treatment failure was found to be significantly predicted by severe canal curvature, multiple canals, and accessory canal morphology. The predictive model performed well (AUC = 0.83).

The study emphasises how pre-operative evaluation of canal shape can accurately predict prognosis and enhance endodontic therapy outcomes.[32]

• **Risk Assessment for Failure or Retreatment**: AI can assess the likelihood of treatment failure or the necessity for retreatment by utilising patient-specific data such as age, systemic health, and root canal architecture complexity. This helps clinicians create better plans for high-risk scenarios.A systematic Predictive Failure Mode Analysis methodology is proposed by Turky and Dummer (2025) to identify multifactorial hazards associated with root canal retreatment failure, including chronic infection, anatomical complexity, and procedural errors.

They stress that retreatment decision-making can be guided by systematic pre-operative risk assessment, which may be aided by AI.[33]

AI-Assisted Clinical Decision Support Systems (AI-CDSS)

These enhance the treatment planning by evaluating large datasets of past clinical cases and patient-specific factors. They use MLM models to create evidence based, customised propositions assisting clinicians in selecting the optimal treatment strategies for complex cases.[34]

In Endodontics, CDSS Can Assist With:

- **Treatment Protocols:** The system suggests optimal treatment strategies based on the patient's symptoms, diagnostic imaging, and clinical history.
- **Alternative Treatment Options:** AI can identify alternative approaches for cases with a higher risk of complications, enabling clinicians to prepare for various scenarios.

The procedure for incorporating AI into endodontic diagnostics is illustrated in the flowchart below (Figure 6).

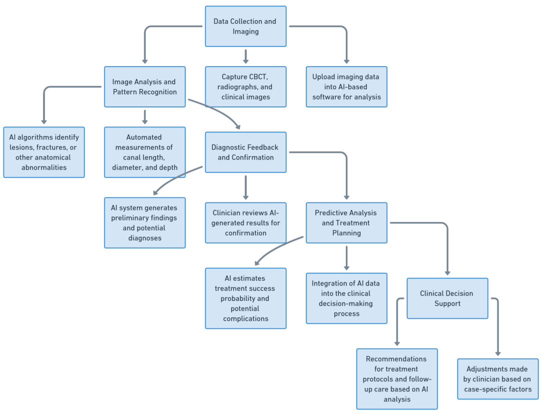

Figure 5: AI-Assisted Diagnostic Workflow

Ekert et al demonstated the ability of a deep learning model to detect periapical radiolucent lesions in panoramic radiographs, differentiating between healthy and diseased regions, with high sensitivity and specificity. This demonstrates how AI may improve treatment outcomes and diagnostic precision. [27]

Digital Records and Health Management Systems in Endodontics

Digital records provide a consistent approach for documenting and monitoring every facet of endodontic therapy, from initial evaluations to aftercare. With their extensive bases for patient data storage, handling, and retrieval, electronic health management systems (EHMS) and digital records have emerged as essential tools in contemporary endodontic practice. By giving clinicians consistent access to crucial information across various case phases and specialities, these systems not only improve collaborative care but also expedite workflow for the storage, management, and retrieval of patient data.[35]

Key Components of Electronic Documentation:

• **Centralised Data Storage:** Case management is made easier by combining patient histories, clinical records, imaging results, and treatment plans into a single digital repository.

• **Integration with Diagnostic Imaging**: Accurate case visualisation is made possible by the smooth integration of digital records and CBCT scans.

• **Improved collaboration and diagnostic support**: Digital records enable endodontists and referred experts to share data in real-time, which promotes integrated care and evidence-based decision-making, particularly in difficult patients.

• **Increased accuracy and efficiency**: Electronic charting tools and treatment templates provide accurate and thorough documentation, lowering the possibility of mistakes and improving overall care quality.

Digital records systems guarantee constant recording of important clinical data, including canal anatomy, instrumentation techniques, and obturation methods, by standardising case documentation. This is crucial for complex, multi-step treatments.[36]

Role of Electronic Health Management Systems (EHMS) in Endodontic Practice

EHMS offers sophisticated capabilities for thorough patient management and clinical workflow optimisation, going beyond simple record-keeping.

- **Appointment Management:** EHMS automates scheduling, sends reminders, and tracks appointments, reducing no-shows and improving patient adherence to treatment plans.
- **Interdisciplinary Collaboration:** Endodontic cases often involve referrals or consultations with specialists like periodontists or oral surgeons. EHMS makes cooperation easy and enhances patient outcomes by facilitating the safe exchange of documents and images.
- **Data Analytics and Reporting:** EHMS can analyze practice data to identify trends, such as treatment success rates or patient demographics. This information helps clinicians refine their techniques and identify areas for professional growth.[37,38]

Below is a flowchart depicting the integration of EHMS with various digital tools in an endodontic workflow, including imaging systems, digital

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records, and patient communication platforms. (Figure 6)

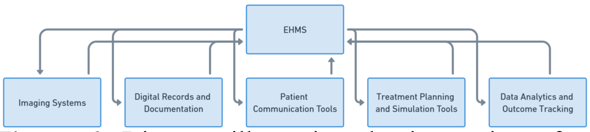

Figure 6: Diagram illustrating the interaction of EHMS with various digital tools in an endodontic workflow, including imaging systems, digital records, and patient communication tools.

In a study whereby through interviews with 35 dental practitioners, it evaluated the demands of dentists about electronic health records (EHRs). The findings showed that 42 needs—including access to X-rays, medical data, patient histories, visual aids, and integrated messaging—were identified across nine themes (15 met, 27 unmet). The results show that there are serious shortcomings in the current EHR systems and that in order to properly support dental treatment, comprehensive, integrated EHR features are required.[36]

Table 1 shows the comparison of various digital technologies in endodontics, highlighting aspects such as technology type, application, advantages, limitations, accuracy, and clinical impact.

Technology	Application	Advantages	Limitations	Accuracy	Clinical Impact
CBCT	3D root & periapical imaging	High-resolution, non-invasive	Radiation, high cost	High (3D analysis)	Better diagnosis & planning
CAD/CAM	Restoration fabrication	Precision, faster workflow	Cost, training needed	High (fit & design)	Efficient restorations
3D Printing	Surgical guides & models	Cost-effective, customizable	Printer/material limits	Moderate–High	Pre-surgical planning
AI Algorithms	Diagnosis & treatment planning	Reduces error, fast analysis	Data-dependent	Variable, improving	Supports complex decision

Table 1: Comparison of various digital technologies in endodontics

Future Directions and Research Needs

As digital dentistry continues to evolve, several exciting areas hold promise for further innovation in endodontics:

- **Developments in AI and Data Integration:** As AI technology advances, it may be anticipated the creation of increasingly sophisticated algorithms that can do automated case documentation, predictive modelling, and early disease identification. Clinical decision-making could be improved and procedures streamlined by combining AI with other digital tools like EHMS and CAD/CAM systems.
- **Creation of biocompatible materials for 3D printing**: More extensive uses of 3D-printed guidance and instruments in healthcare settings will be made possible by ongoing research into biocompatible and sterilisable 3D printing materials. 3D printing will become increasingly more essential in endodontics as a result of these developments.[39]
- **Personalised Treatment Models**: Future endodontic techniques may concentrate on developing highly customised, patient-centered care plans by utilising patient data from EHMS and AI systems. Clinicians' approaches to treatment planning and long-term results may change as a result of predictive and preventive care models.

Even though digital dentistry has many advantages, there are issues that need to be resolved. Significant obstacles still include the high cost of equipment, the requirement for ongoing clinician training, and worries about data privacy. Ethical issues with AI, such as ensuring transparency and obtaining informed patient consent, must also be appropriately addressed in order to maintain trust in new technology. To solve these challenges, industry leaders, regulatory agencies, and the dentistry community will need to collaborate in addition to conducting additional research and teaching.

VI. Conclusion

The adoption of digital technology into routine dental practice has absolutely redefined the endodontic diagnosis, treatment plan and outcome. Some of the mentioned tools like digital imaging, CAD/CAM systems, 3D printing, artificial intelligence, and EHMS have tremendously augmented the diagnostic accuracy, allowing superior treatment and streamlined patient management. These tools provide a simplified and patient focused workflow in conjunction with solving long-term issues in endodontics. Endodontists can tap into these innovations i.e. AI-assisted imaging, CAD/CAM-created tailored restorations, and 3D-printed enhanced surgical guidance to offer more effective care to the patients The future research and development will probably widen the spectrum of digital interventions in endodontics while managing the current challenges including expenses, training, and material shortages.

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