Beyond Explainable Artificial Intelligence: Cognitive Endodontics — Towards Adaptive Clinical Decision-Making

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Statement of the Problem and the Rationale for Introducing the New Concept "Cognitive Endodontics"

Currently, while Explainable Artificial Intelligence (XAI) and Digital technologies like Digital Twin (DT) models have both shown significant potential as standalone innovations, a cohesive framework that integrates these elements into a clinically actionable model for endodontics remains absent. This deficiency may hinder the effective utilization of AI in informing treatment decisions, which is essential for advancing clinical practice. There is a pressing need for an integrative methodology that not only improves predictive accuracy but also enhances transparency, adaptability, and personalized guidance for patients. Such a framework would operate as a true cognitive aid for clinicians, bridging the gap between advanced digital solutions and real-world clinical applications.

Introduction

The integration of AI into dentistry and medicine is revolutionizing various clinical specialties, including endodontics, where existing AI applications range from enhancing imaging diagnostics to improving risk prediction models [1]. AI has shown promise in areas such as radiographic interpretation, canal morphology recognition, and outcome prediction [2]. A critical aspect of AI integration in healthcare revolves around transparency, which is encapsulated in the concept of XAI [3]. XAI is a collection of machine learning methodologies aimed at enhancing the interpretability and transparency of AI models. By elucidating the underlying decision-making processes, these techniques facilitate a deeper understanding of how algorithms arrive at specific outputs, thereby addressing concerns related to model opacity and fostering trust in AI systems [3].

While XAI serves as a necessary foundation, it is a relatively superficial component of AI's potential in endodontics. The next evolution lies in Cognitive Endodontics—a paradigm where AI systems not only elucidate findings but also engage in reasoning, adapt to situational dynamics, and collaborate in real-time with clinicians [4]. This article delineates the Cognitive Endodontics framework, positioning it as a progressive step beyond XAI, aimed at fostering adaptive, patient-centric, and safe clinical decision-making.

XAI as the Foundation

XAI's primary strength is its capacity to render AI predictions comprehensible [5, 6]. For instance, an AI model highlighting untreated root canals in CBCT scans can visually indicate the anatomical regions that influenced its conclusions, thereby augmenting clinician confidence in diagnostic decisions and accountability. The implications for endodontics are significant, offering support in diagnosis, case selection, particularly for challenging situations, such as vital pulp therapy, treatment risk stratification, precision in a range of endodontic procedures, and the detection of bacterial biofilms in intricate canal systems. Furthermore, XAI could enhance patient communication by elucidating risks and expected treatment outcomes through visual representations.

However, the limitations of XAI are evident. While it provides retrospective insights, it lacks adaptability to the non-linear nature of clinical procedures. The complexities surrounding endodontic treatment—such as varying irrigation efficacy, unpredictable bacterial reduction, and dynamic structural preservation—necessitate a more sophisticated framework.

The Cognitive Endodontics Paradigm

Cognitive Endodontics represents the synthesis of XAI with principles of cognitive computing. It enhances transparency by incorporating reasoning, contextual adaptation, and the integration of multimodal data. Key components include [4]:

1. Real-Time Clinical Copilot

Envisioned as an in-the-moment "copilot," AI has the potential to deliver dynamic procedural guidance. For instance, simulations of irrigation flow can be modified in response to real-time changes in canal geometry, alerting clinicians to areas with inadequate disinfection or potential irrigant extrusion risks. This role parallels aviation autopilot systems—supportive, adaptive, and always under clinician control.

2. Continuous Learning Systems

In contrast to static models, cognitive systems possess the capacity for continuous learning from new clinical cases. This iterative improvement enables the AI to adapt to the varying experience levels of individual clinicians, fostering a personalized and evolving support framework.

3. Integration with Digital Twins (DTs)

DTs represent a sophisticated, high-fidelity virtual model of a physical system, encompassing a wide spectrum from complex machinery, such as jet propulsion systems, to intricate biological constructs, like human anatomical structures. These DTs leverage advanced simulations and data integration to replicate the physical behaviour and operational characteristics of their real-world counterparts, facilitating enhanced analysis, optimization, and predictive maintenance [7]. Patient-specific DT models can facilitate the simulation of alternative treatment strategies prior to implementation [7]. Cognitive Endodontics can leverage these simulations in real-time practice, providing predictive insights into canal shaping, irrigation efficacy, and structural preservation strategies.

4. Multimodal Data Fusion

Cognitive systems would amalgamate data streams from CBCT, periapical radiographs, intraoperative sensors, patient history, and biological markers. This comprehensive integration generates a holistic patient profile, forming a more precise basis for treatment decisions than traditional imaging methods alone.

5. Human–Machine Collaboration

Central to Cognitive Endodontics is the principle of augmentation rather than replacement. Clinicians maintain oversight and responsibility, while AI acts as a cognitive partner, enhancing diagnostic precision, optimizing treatment strategies, and improving patient outcomes.

Through the framework of Cognitive Endodontics, the profession is on the cusp of a new era in clinical decision-making that harnesses the strengths of AI to transform and personalize endodontic care.

Cognitive AI within the Context of Healthcare

Understanding Cognitive Endodontics requires its examination within the broader context of cognitive AI's evolution in healthcare. In various medical fields, cognitive AI technologies have progressed from experimental phases to practical applications. For instance, in radiology, XAI models are now integral to imaging workflows, enhancing scan interpretation and mitigating diagnostic errors [8]. In oncology, cognitive AI supports tumour boards by offering personalized treatment options derived from comprehensive data analysis [9]. Similarly, in cardiology, AI systems have demonstrated high accuracy in interpreting echocardiograms and predicting arrhythmias, thereby aiding clinicians in early risk stratification [10]. Medical education has also benefited from AI, with virtual patients and intelligent tutoring systems facilitating adaptive learning environments and realistic clinical simulations [11].

However, in dentistry, particularly in endodontics, the transition to this level of cognitive AI application is in its infancy. Current implementations are predominantly narrow AI solutions focused on specific tasks, such as the radiographic identification of caries, periapical lesions, and root fractures, alongside outcome prediction models [12]. While these tools are beneficial, they offer limited support compared to the holistic, adaptive systems envisioned in Cognitive Endodontics, where an AI copilot integrates biological, mechanical, and procedural data in real-time to inform treatment decisions. The disparity between endodontics and other medical fields can be attributed to technical challenges, such as integrating multimodal data and standardizing clinical datasets, as well as regulatory obstacles.

This comparison emphasizes the novelty and future potential of Cognitive Endodontics. By leveraging insights from advancements in radiology, oncology, cardiology, and medical education, the field of dentistry can transition from narrow diagnostic AI to comprehensive cognitive systems that enhance precision, safety, and personalisation in endodontic treatment.

Clinical translation

The adoption of Cognitive Endodontics could significantly transform clinical practice in several areas:

1. Personalised Risk Assessment: Cognitive systems capable of synthesizing multimodal data could refine the decision-making process regarding vital pulp therapy versus root canal treatment, considering specific biological and structural factors unique to each patient.

2. Adaptive Irrigation and Disinfection: AI-driven real-time modifications to irrigation protocols could maximise bacterial eradication while minimising dentine loss and procedural complications.

3. Enhanced Training and Simulation: Cognitive systems integrated into virtual or augmented reality training platforms could provide real-time feedback to students and clinicians, adapting dynamically to their performance and simulating real-world complexities.

4. Improved Patient Communication: Cognitive models that generate clear visual explanations could enhance communication between clinicians and patients, facilitating informed consent and fostering trust.

Collectively, these opportunities position Cognitive Endodontics within the broader frameworks of precision dentistry, minimally invasive treatment, and regenerative approaches.

The Role of Cognitive Endodontics in Research

Cognitive endodontics, while crucial in clinical practice, holds significant research implications that can transform the understanding of endodontic science. By incorporating principles of AI, adaptive learning, and human decision modelling, cognitive endodontics has the potential to develop innovative frameworks for generating, validating, and translating endodontic knowledge into practice.

A key application of this approach is in the integration of disparate data sources and the generation of hypotheses. Endodontic research spans various domains—microbiology, biofilm dynamics, irrigation fluid mechanics, imaging modalities, and restorative biomechanics—which are frequently examined in isolation. This fragmentation impedes comprehensive insights. Employing XAI models within cognitive endodontics can synthesize these heterogeneous datasets, revealing hidden correlations and facilitating the formulation of new, testable hypotheses. For instance, correlating micro-computed tomography analyses of canal morphometry with antimicrobial efficacy outcomes could unveil predictive relationships that conventional statistical techniques might overlook.

Moreover, cognitive modelling offers a way to simulate clinical decision-making processes. Traditional experimental studies often concentrate on technical performance metrics—like file efficiency or irrigant penetration—while neglecting the nuances of clinician decision-making in uncertain scenarios. By utilizing cognitive modelling, researchers can simulate treatment trajectories, evaluate decision-making errors, and analyse risk tolerance thresholds, thereby enriching translational research with insights into clinical predictability that extend beyond mechanical or biological parameters.

Cognitive endodontics also aligns seamlessly with advancements in DT technology. DTs create patient-specific anatomical and biomechanical replicas, and the addition of cognitive frameworks introduces a "thinking layer," simulating clinician interaction with these models. This integration allows research to assess not just structural and biological outcomes but also the cognitive dimensions of clinical decision-making, enhancing the pursuit of predictive and personalized endodontics.

Furthermore, embedding explainability into AI-driven research models fosters the development of transparent and trustworthy methodologies. As regulatory bodies increasingly require interpretability in AI applications, research framed within cognitive constructs will promote ethical and clinically relevant innovation.

In essence, cognitive endodontics complements rather than replaces traditional research methodologies. It offers a conceptual and methodological framework for exploring the intricate interplay between data, AI, and human cognition. Its application in endodontic research has the potential to accelerate the translation of experimental findings into clinical practice.

Hurdles and Future Perspectives

Despite its significant promise, several challenges must be addressed for the successful implementation of Cognitive Endodontics.

- *Technical challenges:* The integration of heterogeneous data sources into interoperable platforms and the computational demands of real-time adaptation are significant barriers.

- *Ethical challenges:* Maintaining clinician autonomy and ensuring accountability in shared decision-making are critical ethical considerations.

- *Clinical challenges:* Rigorous prospective validation involving diverse patient populations is essential before clinical implementation.

- *Regulatory challenges:* Current regulatory frameworks for the approval and oversight of adaptive AI systems in dentistry are still developing.

Future research should focus on creating hybrid cognitive systems that incorporate explainability, adaptive learning, and DT modelling. Clinical studies are pivotal to evaluate not only the accuracy of these systems but also their usability, clinician acceptance, and patient-centred outcomes.

Conclusion

Cognitive endodontics signifies a paradigm shift in the understanding of endodontic treatment, integrating clinical decision-making with advanced AI, adaptive learning, and the principle of explainability. Its potential in healthcare radiates through AI copilots that enhance diagnostic precision, optimize irrigation and disinfection approaches, and tailor treatment plans—all while upholding transparency and accountability.

Beyond clinical applications, cognitive endodontics delivers considerable value in the realm of research. By enabling the integration of diverse datasets, simulating decision-making in uncertain contexts, and collaborating with digital twin models, it establishes a novel methodological framework for advancing translational endodontic science.

In this dual capacity—as a catalyst for both healthcare innovation and experimental exploration—cognitive endodontics emerges as a foundational concept poised to drive forward innovation, enhance predictability, and promote trust in the digital evolution of endodontic practice.

References

1. S. A. Alowais, S.S. Alghamdi, N. Alsuhebany *et al.*, "Revolutionizing healthcare: the role of artificial intelligence in clinical practice," *BMC Medical Education*, vol. 23, no. 1, p. 689, 2023, doi: 10.1186/s12909-023-04698-z.
2. R. C. Fontenele and R. Jacobs, "Unveiling the power of artificial intelligence for image-based diagnosis and treatment in endodontics: An ally or adversary?," *International Endodontic Journal*, vol. 58, no. 2, pp. 155–170, Feb. 2025, doi: 10.1111/iej.14163.
3. M. Turky and P. M. H. Dummer, "Unleashing the Future of Endodontics: Exploring the Potential Role of Explainable Artificial Intelligence in Risk Stratification and Decision-

Making in Endodontics," *Australian Endodontic Journal: the Journal of the Australian Society of Endodontology Inc*. Australia, Aug. 2025. doi: 10.1111/aej.70010.

4. A. Haleem and M. Javaid, "Role of cognitive computing in enhancing innovative healthcare solutions," *Advances in Biomarker Sciences and Technology,* vol. 6, no. July, pp. 152–165, 2024, doi: 10.1016/j.abst.2024.08.002.
5. D. Muhammad and M. Bendechache, "Unveiling the black box: A systematic review of Explainable Artificial Intelligence in medical image analysis," *Computational and Structural Biotechnology Journal*, vol. 24, no. June, pp. 542–560, 2024, doi: 10.1016/j.csbj.2024.08.005.
6. W. Samek, T. Wiegand, and K.-R. Müller, "Explainable Artificial Intelligence: Understanding, Visualizing and Interpreting Deep Learning Models," 2017, [Online]. Available: http://arxiv.org/abs/1708.08296
7. M. A. Saghiri, J. Vakhnovetsky, and A. M. Saghiri, "The future of digital twins in precision dentistry," *Journal of Oral Biology and Craniofacial Research*, vol. 13, no. 1, p. 19, 2023, doi: 10.1016/j.jobcr.2022.10.003.
8. M. M. M, M. T. R, V. K. V, and S. Guluwadi, "Enhancing brain tumor detection in MRI images through explainable AI using Grad-CAM with Resnet 50," *BMC Medical Imaging*, vol. 24, no. 1, p. 107, 2024, doi: 10.1186/s12880-024-01292-7.
9. K. H. Yu, A. L. Beam, and I. S. Kohane, "Artificial intelligence in healthcare," *Nature Biomedical Engineering*, vol. 2, no. 10, pp. 719–731, Oct. 2018, doi: 10.1038/s41551-018-0305-z.
10. Z. I. Attia *et al.*, "An artificial intelligence-enabled ECG algorithm for the identification of patients with atrial fibrillation during sinus rhythm: a retrospective analysis of outcome prediction," *Lancet (London, England)*, vol. 394, no. 10201, pp. 861–867, Sep. 2019, doi: 10.1016/S0140-6736(19)31721-0.
11. A. A. Kononowicz *et al.*, "Virtual Patient Simulations in Health Professions Education: Systematic Review and Meta-Analysis by the Digital Health Education Collaboration," *Journal of Medical Internet Research*, vol. 21, no. 7, p. e14676, Jul. 2019, doi: 10.2196/14676.
12. C. M. Mörch *et al.*, "Artificial Intelligence and Ethics in Dentistry: A Scoping Review," *Journal of Dental Research*, vol. 100, no. 13, pp. 1452–1460, Dec. 2021, doi: 10.1177/00220345211013808.