Digital Twins Technology in Endodontics: From Reactive to Predictive – A New Frontier Towards Personalized Root Canal Treatment

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Abstract

Objectives To describe the potential of digital twin (DT) technology to enhance personalized root canal treatment (RCT) within endodontics.

Discussion DT models are gaining traction as transformative tools for enabling individualized decision-making across different medical disciplines. These models leverage multimodal patient data to simulate physiological and clinical outcomes. In endodontics, DTs could facilitate the simulation of intricate parameters. The application of DTs will empower clinicians to formulate more tailored treatment plans and improve prognostic predictions. Beyond their clinical applications, DT can enrich research settings, linking laboratory research with tailored patient care. While deploying DTs in endodontics remains largely aspirational, it can shift the paradigm from standardized approaches to personalized treatments. Key challenges to address include data standardization, interoperability among systems, ethical regulations, and the need for specialized clinician training. This article suggests actionable strategies for the translational development of DTs in endodontics.

Conclusion DT models can reshape the vision in endodontics, facilitating real-time, patient-specific simulation and clinical decision-making. Moreover, DTs present a cohesive framework that could enhance precision in endodontic practice while also expediting the translation of research findings into clinical applications. This advancement may lead to the development of personalized and predictive approaches to RCT, significantly improving patient outcomes.

Keywords Artificial intelligence; Clinical decision-making; Digital twin; Endodontics; Personalized medicine; Root canal therapy; Simulation modelling.

Key points

- Digital twins offer the capability for personalized, data-driven simulations that enhance real-time decision-making in endodontic practice.
- Current implementations in cardiology and oncology underscore their efficacy in modelling complex biological interactions and predicting outcomes. In endodontics, DTs could significantly improve diagnostic accuracy, predict disinfection efficacy, enhance clinical techniques, and streamline long-term restorability assessments.
- Successful clinical integration will depend on fostering interdisciplinary collaboration, developing robust data infrastructures, and establishing novel educational frameworks for practitioners.
- Ethical considerations and regulatory compliance are paramount to ensure that the application of DTs in dental practice is safe, transparent, and equitable.

Introduction

Contemporary endodontics is increasingly adopting sophisticated digital tools, ranging from cone beam computed tomography (CBCT) to artificial intelligence-assisted diagnostics. Nevertheless, the current tools often remain static and reactive, providing limited scope for predictive insight. The concept of a digital twin (DT) represents a transformative leap: it embodies a living, learning model reflective of the patient's dentoalveolar system, continuously updated with clinical data to support personalized care and predictive analytics.

Originally emerging from aerospace and manufacturing [1], DTs are gaining prominence in medical applications. Notable implementations include simulating cardiovascular function [2], modelling tumour progression [3], and customizing orthopaedic implants [4]. This article aims to delve into the theoretical foundations that underpin digital technologies in the realm of endodontic care. It seeks to explore various potential workflows that can be enhanced through the integration of these technologies, examining how they can improve efficiency, accuracy, and patient outcomes. Furthermore, the discussion will consider the future potential of DTs in endodontics, highlighting innovative advancements that could reshape clinical practice, enhance diagnostic capabilities, and streamline treatment processes. By investigating these aspects, this article strives to provide a comprehensive understanding of the evolving role of digital technologies in improving endodontic care.

What is a Digital Twin?

A digital twin (DT) is an advanced, high-fidelity virtual representation of a physical system, which can range from complex machinery like jet engines to intricate biological structures such as human organs. DTs are continuously fed real-time data from various sources, including sensors, imaging technologies, and electronic health records, enabling them to accurately reflect the dynamic behaviour of their physical counterpart [5].

In the context of healthcare, the implementation of DTs involves the integration of diverse data streams—such as imaging modalities, genomic data, patient medical histories, and biosensor readings—facilitating real-time, informed clinical decision-making.

In contrast to traditional static digital models or AI algorithms that provide only snapshot analyses, digital twins are interactive and perpetually updated. They have the capacity to simulate the responses of dental structures, such as a tooth or an entire pulp-dentine complex, under various interventions, materials, and pathological conditions. By offering real-time previews of treatment scenarios, DTs significantly enhance the capability of clinicians to make personalized decisions that align with the specific needs of individual patients.

Applications in the Healthcare sector

In the field of cardiology, digital twins (DTs) are employed to model the unique mechanics of individual ventricles, thereby enhancing surgical planning and optimizing postoperative recovery [2]. In oncology, tumour DTs are utilized to simulate tumour growth dynamics and predict patient responses to treatments, thereby providing essential insights for tailoring individualized treatment strategies [3]. In orthopaedics, DTs are leveraged to refine the prosthetic design, ensuring improved fit and functionality for patients [4]. Across these specialties, DTs have demonstrated the ability to enhance patient safety, improve procedural accuracy, and elevate overall treatment outcomes through sophisticated simulations and predictive modelling tailored to individual patient profiles.

Potential Applications in Endodontics

1. Patient-Specific Root Canal Anatomy Simulation

Leveraging advanced imaging modalities such as Cone Beam Computed Tomography (CBCT) and intraoral scanners, combined with sophisticated segmentation algorithms, DTs can generate a dynamic, three-dimensional reconstruction of the individual pulp-dentine system. Such a model would support the simulation of customized access cavity strategies, instrumentation selection and manipulation, and canal-filling techniques, significantly mitigating procedural errors in complex anatomical scenarios prone to mishaps.

Recent advancements in imaging and navigation technologies have significantly enhanced the precision of translating patient-specific root canal anatomy into clinical practice, as evidenced by numerous studies [6, 7, 8, 9, 10, 11, 12, 13, 14]. A pivotal advancement in this area is the development of customized access cavity strategies, leveraging both static and dynamic guided endodontic techniques. These approaches enable clinicians to navigate complex canal anatomies while minimizing dentine removal and maximizing precision [6, 7, 8, 9, 10, 11, 12, 13, 14].

Static guides, which are fabricated from CBCT datasets, have shown remarkable effectiveness in locating calcified canals and designing conservative access cavities [7, 12, 13]. Meanwhile, dynamic navigation systems provide real-time feedback and adaptability, enhancing procedural accuracy and reducing the risk of iatrogenic complications [9, 12]. Collectively, these strategies exemplify the powerful integration of digital technologies with anatomical data, laying the groundwork for patient-specific simulations. This foundation may be further refined by employing digital twin models, which facilitate virtual testing of access designs prior to their implementation in clinical settings.

2. Microbial Biofilm and Healing Prediction Models

By integrating patient-specific microbial profiles, immune responses, and systemic health data from electronic health records, DTs enable predictive modelling for biofilm resilience and periapical healing trajectories. This capability will permit clinicians to modify antimicrobial approaches in real time, enhancing treatment effectiveness aligned with the infection's evolving status and facilitating expedited healing processes.

3. Disinfection Protocol Optimization

Digital technologies offer the potential to evaluate various disinfection protocols by simulating their effectiveness against distinct microbial compositions within a patient's root canal ecosystem. A deeper understanding of the interactions between disinfectants and established biofilms in real-time empowers clinicians to refine their disinfection strategies, thereby increasing the likelihood of successful treatment outcomes.

4. Monitoring of Endodontic Files

Creating a sophisticated digital twin of a nickel-titanium (NiTi) endodontic instrument, which continuously receives real-time measurement data from the physical file while it operates, could facilitate the generation of an accurate thermal map that represents the instrument's performance under various working conditions [15].

By leveraging advanced computational modelling and data analytics, this virtual representation can be compared to the actual thermal dynamics observed in the physical file. This comparison will enable the identification of any anomalous trends or deviations from expected performance. Such insights are vital for the early detection of potential issues, such as excessive wear or fatigue, which could lead to instrument fractures during procedures. Ultimately, the goal is to enhance the safety and efficacy of root canal treatments by minimizing the risk of instrument failure and improving patient outcomes [15].

5. Long-term Restoration Evaluations

By modelling the long-term behavioural outcomes of the diverse range of materials used in root canal treatment, DTs can forecast the durability and success rates of restorations over extended periods. By simulating various post-treatment scenarios, dentists will be better positioned to make informed choices regarding material selection and restoration strategies, ultimately ensuring improved long-term success for patient outcomes.

Finite Element Analysis (FEA) plays a critical role in the field of dentistry, particularly in examining the biomechanical behaviour of root canal-treated teeth across various restorative scenarios. This technique allows for sophisticated, non-destructive simulations that detail stress distribution within both tooth structures and restorative materials, offering valuable insights into the impact of factors such as access cavity design, canal preparation, and coronal restoration on long-term dental outcomes [16]. By incorporating FEA into digital twin frameworks, we can move beyond simplistic models to create patient-specific biomechanical simulations. This advancement facilitates the development of personalized restorative strategies, ensuring optimized function and enhanced longevity of dental restorations.

6. Follow-up and Prognostic Simulation

A digital twin, continuously updated with radiographic images, intraoral photographs, and detailed clinical findings gathered after treatment, offers significant advancements in the simulation of future periapical responses. The technology not only enables the projection of potential outcomes based on a patient's unique dental profile but also plays a crucial role in the early detection of complications. By analysing trends and patterns in the data, the digital twin can identify early signs of treatment failure, such as increased bone resorption or changes in radiographic appearance. This predictive capability will allow clinicians to intervene proactively, implementing preventive measures to mitigate the risk of complications. Consequently, the integration of this sophisticated simulation tool into routine practice can enhance patient outcomes and optimize treatment strategies.

Challenges and Requirements for Translation in Digital Twin Development

Effective execution of DTs in endodontics necessitates addressing numerous translational issues. These issues encompass technical, regulatory, ethical, and educational aspects, highlighting the need for substantial collaborative efforts among technology developers, researchers, and clinicians.

1. Data Infrastructure and Interoperability

DTs in endodontics depend on comprehensive, multi-source datasets. These datasets include cone-beam computed tomography (CBCT) images, detailed clinical records, the results of microbial testing, and advanced intraoral imaging techniques. Establishing robust standards for data interoperability is crucial; this would allow seamless integration with electronic dental records, ensuring that clinicians can access and utilize unified patient information. Strengthening data infrastructure entails the development of decentralized systems that facilitate data sharing while maintaining security and compliance with health regulations.

Sensors built into high-speed handpieces will enhance the precision of access cavity preparation by recording real-time data on the spatial orientation of the handpiece relative to the pulp chambers, preserving a critical amount of tooth structure. Similarly, torque sensors within engine-driven file systems will capture stresses exerted on instruments during root canal instrumentation. This will enable the clinicians to recognize risky moments for instrument distortion and fracture. When combined with clinical and imaging documentation, data stemming from such sensors will be able to considerably underpin the real-time accuracy of DTs. Such sensor incorporation has been implemented in cardiology, where surgical navigation systems utilize feedback from real-time sensors for intraoperative planning [2].

2. Computational Models and Validation

The creation of reliable biomechanical, fluid dynamic, and biological simulations of the root canal system will necessitate an interdisciplinary approach. Collaboration among engineers, dentists, data scientists, and biologists is vital to developing sophisticated models that accurately reflect real-world scenarios. Clinical validation will further provide the necessary evidence of the efficacy and safety of these models [17]. This process will not only require extensive computational simulations but also the integration of clinical feedback to refine model parameters continuously.

3. Ethical and Privacy Considerations

The utilization of DTs involves the collection and analysis of extensive personal health data, which raises significant concerns surrounding data privacy, informed consent, and accountability of algorithms. As highlighted by Topol (2019), establishing clear and robust governance frameworks is imperative to address these ethical challenges [18]. This includes developing transparent consent processes for patients and implementing stringent data protection measures to safeguard sensitive information from unauthorized access and misuse. Moreover, ongoing audits and assessments of algorithmic performance must be conducted to ensure they function equitably and transparently within clinical contexts.

4. Education and Clinician Engagement

Incorporating DTs into clinical practice necessitates a shift in the educational paradigm for dental professionals. To enhance clinician literacy regarding digital health tools, educational modules focused on the interpretation of simulations, integration of interdisciplinary approaches, and the ethical use of technology will need to be embedded into both undergraduate and postgraduate curricula [19]. Programs that foster hands-on experience with digital technologies are essential, enabling clinicians to become proficient in the use of DTs and to appreciate their potential impact on patient care.

Precedents facilitate the application of DTs in Endodontics

While DTs are still aspirational, several advancements in the field of endodontics demonstrate foundational capabilities:

1. The ability of AI-based diagnostics, like Diagnocat AI (Diagnocat, Miami, Florida, USA), to identify periapical lesions on radiographs suggests the possibility of AI-driven diagnostic layers in DTs in the future.
2. Dynamic navigation systems have the potential to optimize access cavity trajectories by combining CBCT data and real-time handpiece tracking.

3. FEA can support DT biomechanical modelling by mimicking the mechanical responses of teeth to occlusal forces.
4. Similar to fluid dynamics simulation in DTs, irrigation platforms such as GentleWave (Sonendo, Laguna Hills, California, USA) can replicate fluid motion in the root canal.
5. Incorporating electronic dental records with CBCT, such as Romexis (Planmeca, Helsinki, Finland) can offer multi-modal clinical data that is essential for real-time updating and twin concurrence.

Digital Twins in Endodontic Research: A Paradigm Shift

The clinical potential of digital twins in endodontics is promising, however, their most immediate and profound application is in research settings. Digital twins offer a computational infrastructure that enables researchers to model intricate biological systems, test hypotheses *in silico*, and validate clinical interventions prior to real-world application. Recent advancements underscore how digital twin methodologies are poised to transform endodontic research.

Monte Carlo Simulations for Optical Properties of Dental Tissues

Monte Carlo simulation has established itself as the benchmark for modelling light transport in biological tissues, effectively capturing the stochastic interactions of photon scattering and absorption. Within dentistry, these methods have been deployed to explore transillumination and optical scattering characteristics in enamel, dentine, and pulp tissues, thereby facilitating the assessment of lesion detection and pulp status [20]. The integration of Monte Carlo simulations into digital twin frameworks allows for the real-time simulation of optical diagnostic tools, significantly enhancing our comprehension of light-tissue interactions within the complex anatomical and physiological landscape of teeth. By aligning Monte Carlo-based optical predictions with individual patient imaging, digital twins can generate personalized optical models that improve the precision of non-invasive diagnostic methodologies.

Digital Optical Twins (DOT) for Pulp Vitality Assessment

The notion of DOT has recently emerged for evaluating the condition of the pulp [21]. Unlike traditional thermal or electric pulp tests, which often yield indirect and potentially misleading results, DOT can simulate how dental tissues respond optically to controlled external stimuli, creating a virtual representation of pulp status. These models incorporate physiological parameters such as blood flow, oxygenation levels, and the scattering properties of dentine, offering a more relevant diagnostic basis. This innovation not only promises advancements in non-invasive diagnostic techniques but also establishes a robust research platform for evaluating and refining disease assessment tools prior to their clinical application.

Broader Implications for Endodontic Research

Digital twin methodologies have far-reaching applications beyond optical assessments in endodontics. For example, computational modelling can be harnessed to simulate the dynamics of irrigants, microbial behaviour in biofilms, or tissue regeneration processes in regenerative endodontics. By amalgamating multi-scale biological data into digital replicas, researchers can systematically investigate new interventions, optimize treatment protocols, and minimize reliance on invasive or ethically sensitive experimental approaches.

In summary, these insights reveal that digital twins extend beyond mere clinical aspirations; they are actively propelling forward the frontiers of endodontic research through simulation-driven exploration. The interplay of Monte Carlo optical simulations and DOT exemplifies how computational twins validate innovative diagnostic and therapeutic approaches, effectively bridging the divide between laboratory research and patient-centred clinical applications.

Future Directions

While no Digital Twin systems are presently in operation within endodontics, successful implementations in fields such as cardiology and orthopaedics indicate a promising future for the possible application of this technology. Initial prototypes could focus on narrow applications, such as simulating root canal shaping or predicting periapical healing, slowly evolving into more comprehensive models that encompass the entire aspect of dentoalveolar health and patient wellbeing.

In addition to clinical applications, these systems may serve as tools for patient education, offering visual and interactive explanations of dental diseases and anticipated treatment outcomes. The ultimate goal of implementing DTs in endodontics is to shift from a reactive approach to a predictive one, enabling clinicians to simulate potential treatment outcomes before invasive procedures are conducted. By doing so, DTs can enhance patient outcomes and improve decision-making in endodontic care.

Integrating digital twins into research frameworks significantly enhances the field of endodontics by creating a direct link between experimental research and clinical application. Techniques such as Monte Carlo simulations for optical property analysis and the use of Digital Optical Twins to evaluate pulp status illustrate how these virtual models can expedite innovation by allowing for the validation of diagnostic methods and therapeutic concepts prior to clinical implementation. This bifunctional approach—improving research methodologies while refining clinical precision—establishes digital twins as a transformative paradigm in endodontics. They not only facilitate personalized treatment planning but also contribute to the scientific underpinnings of future advancements in endodontic care.

Conclusion

The integration of digital twin technology into endodontics presents a transformative opportunity to advance personalized patient care and improve clinical decision-making. Digital twins—virtual replicas of physical entities—can facilitate a deeper understanding of the dental anatomy and treatment responses of individual patients. This innovation allows practitioners to simulate treatment outcomes, enabling more precise and tailored approaches to endodontic therapies.

In addition to advancing clinical decision-making, digital twins are set to play a pivotal role in research applications within the field. Techniques such as Monte Carlo simulations for light propagation and the utilization of Digital Optical Twins for assessing pulp status demonstrate their effectiveness in validating innovative diagnostic and therapeutic approaches ahead of clinical implementation. As their dual functionalities continue to develop, digital twins are positioned to transform endodontics into a domain where precision, personalization, and predictive analytics converge. This evolution promises to bridge the gap between research discoveries and tailored patient care, further enhancing the integration of scientific innovation within clinical practices.

Despite the promising potential, several challenges must be addressed for these technological advancements to be fully realized. These include ensuring the accuracy of data collection, addressing patient privacy concerns, and integrating digital twins into existing clinical workflows. Furthermore, fostering interdisciplinary collaboration among dentists, data scientists, and engineers is crucial, as diverse expertise will be necessary to develop robust systems that can reliably interpret complex dental health data.

By systematically tackling these obstacles and promoting teamwork across various fields, the dental community can lay a solid foundation for a future where predictive, individualized treatment becomes commonplace. Such a shift not only aims to enhance the efficiency and effectiveness of endodontic procedures but also to significantly improve patient care and outcomes in this critical area of dentistry.

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