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Digital twin technology in dentistry: A review

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Abstract:
Digital twin technology (DTT) is an emerging innovation in dentistry that enables virtual representation of individual patients. It integrates intraoral scans, CBCT data, deep learning, sensor inputs and finite element analysis to create dynamic patient models. These models support personalised treatment planning, procedural guidance, error reduction and remote patient monitoring. Clinical implementation remains challenging due to high costs, data integration, privacy concerns, secure data transfer and real-time accuracy. Thus, DTT's potential to advance predictive, personalised dental care while identifying barriers requiring further research is reviewed.

Keywords: Digital twin (DT), bi-directional, dynamic, artificial intelligence (AI), dentistry

Background:
The term Digital Twin (DT) was first coined by John Vickers of the National Aeronautics and Space Administration in the early 1990s, while its concept was first developed by Michael Grieves in 2002 **[1].** Fundamentally, a DT is a virtual replica of a real object or phenomenon **[2].** This replication distinguishes itself from traditional simulations through its predictive abilities and two-way data sharing, in which physical sensors transfer live data to a central system that continuously relays useful information to the real objects **[3].** Advancements in intraoral scanning, cone beam computed tomography (CBCT) and artificial intelligence (AI)-driven biomechanical solvers introduced dedicated dental DT applications in 2020 as an innovative tool that is set to shape the future of patient-centred care in dentistry **[4, 5].** The understanding of the timeline of Digital Twin Technology (DTT), from conception to dental application, is necessary for contextualising current capabilities and setting realistic expectations for the pace of further refinement across various fields of dentistry **[3].** The structure of the oral cavity and its conditions are virtually duplicated using dynamic, real-time patient data, imaging and finite element modelling, allowing for real-time adjustments based on actual patient responses to optimise diagnoses, personalise treatment procedures and enhance patient outcomes **[6].** It has applications in orthodontic treatment by tracking tooth movement, predicting brace designs and minimising patient visits. Moreover, it facilitates prosthodontic interventions for patient-specific prosthetic designs and implant planning and, in endodontics, material selection and prediction of potential complications. In oral and maxillofacial surgery, procedures can be performed virtually by replicating complex craniofacial anatomy and patient-specific miniplates can be designed and manufactured. Thus, DTT predicts and adapts treatment plans to help achieve personalised, minimally invasive and efficient dental care **[7].** Although DTT has been shown to profoundly impact various fields of dentistry, it requires further advancement in standardising data systems, ethical and regulatory frameworks and comprehensive mapping **[8].** Therefore, it is of interest to evaluate the present state of DTT in dentistry and the need for interdisciplinary collaboration to attain a clinically practical and universally acceptable DT integration into standard dental workflows.

Data acquisition and digital model construction:
In dentistry, the creation of a high-fidelity DT marks a significant change from static 3D representation to a dynamic, multi-dimensional simulation of a patient's anatomical and biological reality **[9].** It starts with collecting multi-modal data, which bridges the gap between digital intelligence and the physical world. While traditional dental records provide fragmented snapshots, DT requires the complete integration of data streams, with anatomical surface data obtained through intraoral scanning serving as the foundational layer **[10].** It produces a dense triangulated mesh of the gingiva and dentition with micron-level accuracy by using optical triangulation **[11].** However, a genuine twin requires more than just surface data. Practitioners use CBCT to gather volumetric Digital Imaging and Communications in Medicine (DICOM) data that reveal internal details such as bone density and root morphology. In complicated cases, Magnetic Resonance Imaging (MRI) is added to provide a complete skeletal and soft-tissue framework by capturing the minute details of the temporomandibular joint (TMJ) soft tissues **[12].** The steps proceed to data processing and image segmentation when these raw data streams are gathered. Raw DICOM and Stereolithography (STL) files are disorganised collections of voxels and points that need to be taught what they represent. The system uses Convolutional Neural Networks (CNNs), a type of AI, for automatic segmentation to distinguish between cortical bone, dentin and enamel **[13].** After that, Point Cloud Registration unifies different datasets into a single

coordinate system. The virtual model attains full accuracy by combining the high-resolution surface mesh from an intraoral scan onto the volumetric bone data from a CBCT, enabling doctors to observe how surface tooth movements affect underlying bone support. This registration must be thorough to prevent artifacts that lead to surgical and prosthetic errors. The addition of biological and dynamic data causes a three-dimensional (3D) model to become a functional DT. Clinicians use digital jaw tracking to document each patient's distinct functional envelope and mandibular circuits because a static model cannot predict how a patient chews**.** The twin's live quality is captured here. Additionally, Finite Element Analysis (FEA) is more commonly used to make virtual models testable. Adding physical characteristics, such as the periodontal ligament's elasticity, enables clinicians to simulate biomechanical stress and strain before physical intervention **[14].** For instance, a dentist can load a virtual implant into the twin to forecast bone remodelling over several years. Finally, the creation of a DT features a bidirectional feedback loop. Unlike a conventional dental model, which is discarded after treatment, the DT is a living document that can receive real-time updates from wearable sensors or smart toothbrushes via the Internet of Dental Things (IoDT) **[15].** As a patient ages or undergoes physiological changes, the twin adjusts accordingly. Thus, the final build of a digital DT involves the synthesis of biomechanical modelling, real-time biological data and geometric precision, resulting in a predictive tool that benefits the patient throughout their clinical lifespan. This multi-layered strategy guarantees that the twin serves as a predictive engine for personalised clinical innovation rather than just a mirror image**.**

Clinical applications in dental practice:

DT has demonstrated promising applications across multiple dental specialties, including endodontics, orthodontics, implant dentistry, periodontics and orthognathic surgery, by enabling procedural simulation, predictive analytics, real-time monitoring and personalised treatment planning. In endodontics, DTT is increasingly being explored for personalised root canal treatment planning and procedural guidance. Patient-specific virtual models generated from CBCT scans, intraoral imaging and clinical data allow clinicians to simulate procedures and assess complex root canal anatomy before treatment, thereby improving precision and reducing potential complications **[16].** The PriciGuide™ system, a sleeve-less, patient-specific guide, uses digital twin data to perform minimally invasive access cavity preparation **[17].** Preliminary findings indicate that it may enhance procedural precision in the management of calcified canals; however, current evidence remains limited and is based on case reports. DTT has become a transformative application in orthodontics by overcoming the limitations of conventional two-dimensional cephalometric analyses, including landmark identification errors, observer variability and anatomical superimposition. The DTT creates virtual models that serve not only as advanced diagnostic tools but also as predictive simulation platforms for assessing orthodontic tooth movement, skeletal modifications and treatment outcomes before clinical intervention. In implant dentistry, DTT enables the development of patient-specific virtual environments that enhance treatment planning and surgical accuracy. DT systems can simulate implant positioning, evaluate bone quality, assess stress distribution and analyse implant-bone interactions before surgical procedures **[18].** Through FEA and biomechanical modelling, clinicians can optimise implant design, personalise implant selection and predict long-term treatment outcomes according to individual anatomical characteristics **[19].** Such predictive virtual models have the potential to reduce complications and improve implant success rates. DTT is increasingly being explored in periodontics to support personalised diagnosis, disease prediction and treatment planning by integrating clinical findings, radiographic data, periodontal measurements and patient-specific biological information **[20]**. DT models can simulate periodontal tissue responses and predict disease progression, enabling clinicians to identify individuals at higher risk and tailor preventive or therapeutic interventions accordingly **[21].** Furthermore, by incorporating computational and causal modelling approaches, DT systems may forecast healing patterns and treatment outcomes, facilitating precision-based periodontal care and longitudinal monitoring. DTT has also shown potential in orthognathic surgery by creating patient-specific virtual models from CBCT data, facial scans and dental imaging. These systems allow clinicians to simulate skeletal movements and forecast postoperative facial and functional outcomes before surgery **[22].** Such predictive simulations support treatment optimisation, improve surgical precision and facilitate better interdisciplinary treatment planning and patient communication. As integration with AI and real-time data analytics continues to advance in dentistry, DTT signifies the potential to reshape clinical workflows and improve diagnostic accuracy, treatment predictability and patient-centred care across dental specialties.

Comparison with conventional and other digital models:

The landscape of clinical dentistry is undergoing a profound transformation, shifting from reactive treatments to proactive, data-driven precision. At the core of this evolution is the DT, a dynamic virtual replica of physical biological systems **[22].** Understanding the technical distinctions between DTs and conventional modelling frameworks, such as Computer-Aided Design (CAD), Building Information Modelling (BIM) and traditional simulations, is crucial for implementing next-generation dental applications. When comparing Digital Twins with CAD, it is important to recognise that digital dentistry has historically relied heavily on CAD for designing prosthetics and surgical guides. While CAD excels in creating highly precise geometric shells and initial 3D models, it is fundamentally static. Once a CAD file is exported for manufacturing, its role ends; it cannot adapt to how a physical object functions over time. The integration of a Digital Twin transforms these static CAD models by connecting them to real-world data, allowing the digital model to evolve and optimise the physical counterpart throughout its entire lifecycle **[23].** A similar paradigm shift

occurs when examining BIM. BIM functions as a specialised form of CAD that incorporates more than just geometry; it also includes metadata on time, costs, operations and maintenance. However, BIM models are typically static 3D documentation that requires manual updates during the design and construction phases **[24].** In stark contrast, a DT is defined by an automated, bi-directional data flow. A DT often utilises the geometric foundation of a BIM or CAD model but connects it to the physical world using Internet of Things (IoT) sensors, creating a dynamic, living replica that continuously updates with real-time data **[25].** Furthermore, Digital Twins diverge significantly from traditional simulations. Researchers frequently use traditional simulations to test hypothetical "what-if" scenarios. However, these simulations rely on predefined, historical datasets and operate in isolated batch processes. They represent a one-way feedback loop primarily used during the initial design phase. A DT, however, is a dynamic entity that shows what is happening in real time by utilising continuous feedback. Instead of rigid, static tests, digital twins feature fully integrated, bidirectional data exchange, meaning changes in the physical entity instantly update the digital model, which can then regulate and optimise the physical system. This real-time adaptability allows for significantly faster and more accurate decision-making than traditional simulations **[26].** By moving beyond static datasets and hypothetical testing, DTT establishes a new, dynamic standard for precision analysis and treatment planning.

Ethical, legal and data governance considerations:

The integration of DTT into dental practice introduces far-reaching ethical, legal and data governance challenges that must be addressed alongside its clinical potential. As virtual replicas of a patient's orofacial anatomy are constructed from 3D imaging, intraoral scanning and AI-driven analytics, the resulting digital models aggregate highly sensitive biometric and health data, warranting rigorous scrutiny of how such information is collected, stored, used and protected **[27].** Central to the ethical discourse is the principle of informed consent. Conventional dental consent frameworks were designed for discrete clinical interventions and are inadequate for AI-assisted workflows in which patient data may be continuously processed, re-analysed, or shared across platforms. Emerging guidance indicates that patients should be explicitly informed of the role, capabilities and limitations of AI tools contributing to their care and that AI should be framed as a clinical adjunct operating under professional supervision rather than an autonomous decision-maker **[28].** Closely related is the question of data ownership: when proprietary AI software generates a digital twin from a patient's anatomical data, the resulting model may embed both patient-generated and AI-generated content and the distribution of ownership rights among the patient, clinician, institution and technology vendor remains legally unresolved in most jurisdictions. Algorithmic bias represents a serious and underappreciated ethical risk. AI models trained on non-representative datasets may perform inequitably across racial, ethnic, or socioeconomic subgroups, compounding existing health disparities. Research in orthodontics has specifically demonstrated that machine learning models can accentuate racial inequalities when trained on demographically skewed data **[29].** Transparency and explainability are therefore ethical imperatives: clinicians and patients must be able to meaningfully interrogate the basis for AI-derived recommendations, particularly when these influence irreversible clinical decisions **[30].** From a legal standpoint, DTT implementation in dentistry is governed by overlapping data protection frameworks. In the United States, the Health Insurance Portability and Accountability Act (HIPAA) mandates minimum safeguards for protected health information, while the European Union's General Data Protection Regulation (GDPR) imposes stricter obligations including explicit consent, data minimisation and mandatory impact assessments for high-risk AI processing **[31].** The Regulation (EU) AI Act (2024) further classifies AI systems used in clinical settings as high-risk, requiring conformity assessments, technical documentation and sustained human oversight **[32].** Liability attribution in the event of an AI-assisted diagnostic error remains a contested area of law; determining whether responsibility lies with the clinician, institution, or technology developer is complicated by the opacity of many deep learning systems and the absence of established legal precedent. Data governance considerations are equally critical. Digital dental datasets, encompassing CBCT images, 3D surface scans and longitudinal treatment records, pose substantial cybersecurity challenges, particularly as DTT platforms increasingly rely on cloud infrastructure and IoT-connected devices, which expand the potential attack surface. End-to-end encryption, role-based access control and audit logging are essential technical safeguards. Blockchain technology has been proposed as a promising governance infrastructure for dental health data, offering immutable audit trails, decentralised storage and patient-controlled access permissions that could address interoperability and security shortcomings of conventional centralised systems **[33, 34].** Standardisation of data formats and interoperability protocols across imaging systems and practice management platforms is equally necessary to ensure data quality and continuity of care. At the level of clinical practice, these considerations converge on the relationship of trust between clinician and patient. Surveys indicate that standardised AI consent procedures significantly improve patient communication and confidence when the clinician's oversight role is clearly articulated **[34].** Professional bodies and regulatory authorities must therefore develop context-specific ethical guidelines, training requirements and governance frameworks tailored to the unique data environment of digital dentistry. Ultimately, the responsible deployment of DTT depends not only on technological capability but on the profession's commitment to patient autonomy, equitable care and rigorous accountability, foundations without which the clinical promise of digital dental twins cannot be ethically realised **[35-37].**

Conclusion:

Digital twin technology enables personalised dental care through patient-specific virtual models. Clinical adoption

remains limited by cost, data integration, cybersecurity and regulatory challenges. Further research is needed to establish safe, ethical and effective implementation in dentistry.

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