

Digital Twins in Dentistry: Technological Foundations and Clinical Applications

Choncharoen Thamsopinkull*

Faculty of Dentistry, Nation University, Chiang Mai, 50210, Thailand

* Corresponding author. E-mail address: choncharoen_th@hotmail.com

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Abstract

Digital twins have become a powerful new trend in dentistry, enabled by advancements in multimodality imaging, artificial intelligence (AI), and numerical simulation. Dental digital twins are living, data-driven virtual counterparts to a patient's oral and craniofacial anatomy that allow real-time modeling, prediction, and optimization of clinical treatment. This review aimed to gather current knowledge about technical concepts, clinical fields, limitations, and future challenges of digital twins in dentistry. These key enabling technologies (including cone-beam computed tomography, intraoral scanning, facial surface imaging, and deep learning-based segmentation) contribute to accurate anatomical reconstruction and the generation of automated models. From a clinical perspective, digital twins appear particularly promising for implant planning, simulation of orthodontic treatment and orthognathic surgery, and patient communication. Research suggests that this technology may improve accuracy, workflow efficiency, and patient involvement. Many challenges, however, persist in regard to insufficient clinical validation; poor interoperability; high infrastructure requirements and authority issues in data access use cases. New modalities such as Internet of Things (IoT)-driven monitoring, blockchain-verified data sharing, and the integration of genomic information with biomechanical models may expand the range of applications for dental digital twins, enabling precision dentistry. Despite significant progress, digital twins are a developing technology. Scalability for clinical use will require robust evidence, standardized protocols, regulatory guidance, and ethical and societal considerations. Digital twins have significant potential to transform practice, education, and research in dentistry, but their benefits could be widespread only with responsible development and broad clinical evaluation.

Keywords: Digital twins, Digital technology, Dentistry, Digital dentistry, Artificial Intelligence

Introduction

Dentistry is currently undergoing a tremendous digital revolution, which is fed by several emerging and innovative new technologies that are radically changing the scenario in clinical approaches, educational strategies, and global patient experience. Of these innovations, digital twins appear to be the most promising and disruptive paradigm (Salvi et al., 2025). Digital twins are described as sophisticated virtual replicas of real physical assets or complex systems, and can combine, in real-time, data with advanced models which result in dynamic and very accurate representations of the actual objects or systems. In the narrow field of dentistry, these digital twins offer unprecedented potential for improved diagnosis, detailed treatment planning, delicate surgical simulation, and highly personalized patient care (Thiribhuvanan et al., 2025).

This comprehensive literature review summarizes the current status, various applications, and future trends of digital twins in dentistry. In contrast to past reviews, which have tended to focus on either technological frameworks or general healthcare applications, this review specifically integrates clinical dental applications with emerging digital technology advancements and ethical considerations. By providing a multidisciplinary perspective, this review aims to integrate theoretical development and practical implementation in dentistry. Furthermore, this review highlights unresolved challenges and identifies key directions for future research and clinical translation.

Content

1. Definition and Core Concept of Digital Twins in Dentistry

In the field of dentistry, a digital twin can be used to understand the oral and maxillofacial structures of a person, reconstructed with data from varied sources, including three-dimensional (3D) imaging technology, intraoral photography, surface scans for facial expressions (and occasionally motions), as well as observations on changes which signal how beforehand they are likely to occur. These virtual models are continually updated with real-time data to mimic their physical counterparts in high fidelity (Jan et al., 2025).

In contrast to static digital models, genuine digital twins maintain a lively, bidirectional relationship with the physical system, enabling real-time monitoring and predictive analytics that can anticipate future failures of equipment, such as valves or hydraulic lines. This may be hard to visualize, but this is the general idea (Ringeval et al., 2025).

Establishing a digital twin in dentistry generally involves several steps: obtaining multimodal imaging data, anatomical structural segmentation and reconstruction, mathematical modeling of physiological and mechanical processes, and lastly, integrating all of this information into a comprehensive virtual environment (Iliuță et al., 2025). This process translates raw imaging data into clinically feasible treatment and diagnostic advice, and provides points from which to make informed decisions for change.

2. Technical Foundations and Implementation

2.1 Imaging Technologies

The foundation of digital dental twins is high-performance imaging tools. Cone beam computed tomography (CBCT) remains a primary tool for 3D data acquisition, as it produces detailed volumetric images and delivers acceptable radiation doses to hard tissues (Fuglsig et al., 2024). However, adding CBCT information to the complementary technologies already established improves the accuracy of digital twins. 3D Facial surface imaging capture (face scan) systems depict soft tissue geometry in photorealistic detail, which can be used to provide complete reconstructions of craniofacial anatomy (Singh et al., 2024).

Intraoral scanning is another critical technology for the development of digital twins, as these systems can create highly detailed digital impressions of dentition and periodontal tissue (Kumar et al., 2024). Intraoral scanner accuracy and precision also depend on the device; comparisons between intraoral scanners have shown that different systems may be more appropriate for specific clinical applications (Cho et al., 2023).

2.2 Data Integration and Modeling

Data integration information and models are among the requirements for creating clinically useful digital twins, integrating heterogeneous data source types. Virtual treatment simulation using digital smile design and digital wax-up technology is currently the most popular application in dental diagnostics (Joda et al., 2024). These methods allow both dentists and patients to foresee treatment results with a degree of accuracy that is truly remarkable before actual clinical performance occurs.

Deep learning and machine learning algorithms have enhanced digital twin capabilities in several ways. Specifically, by automating tasks for segmentation and extracting critical information from complex image data. However, the digital twin can better approximate reality than ever before. Deep learning-based segmentation of single teeth and bone structure, including subtle features such as the periodontal ligament interface, enables the production of anatomically correct models suitable for biomechanical simulation (Xu et al., 2023). These automated approaches reduce current reliance on manpower, while guaranteeing more uniform results and reducing hand time accordingly, as reported in the publication (Bonny et al., 2024).

3. Clinical Applications of Dental Digital Twins

3.1 Implant Planning and Surgical Guidance

One of the most extensively studied applications of dental digital twins is implant planning, particularly in prosthodontics and oral implantology. Digital twins are utilized for site-specific implant planning, including the assessment of bone quality and quantity, optimization of implant positioning, and prediction of occlusal load distribution for preoperative planning. By integrating patient-specific imaging data—such as cone-beam computed tomography (CBCT)—with biomechanical modeling, clinicians can simulate stress distribution around proposed implant sites and refine treatment strategies accordingly (Ahn et al., 2024). This technology shifts implant planning from experience-based to patient-specific, evidence-based optimization.

Beyond preoperative planning, digital twins also support guided implant surgery by integrating virtual treatment planning, computer-aided design and manufacturing (CAD/CAM), and real-time navigation systems. These technologies enable the fabrication of patient-specific surgical guides and facilitate accurate transfer of the virtual plan to the operative setting. Compared with conventional freehand techniques, such approaches have been associated with improved positional accuracy, reduced intraoperative deviation, and enhanced primary implant stability (Kafedzhieva et al., 2025). This integrated set of methods is where the leading edge is now located in the digital transformation of implant dentistry.

3.2 Orthodontic Treatment Planning and Monitoring

Digital twins enable comprehensive orthodontic treatment planning by simulating tooth movements and modeling treatment outcomes (K DI Cosola et al., 2025). When digital twins are combined with computer-aided design and manufacturing (CAD/CAM) technologies, the duration of overall orthodontic treatment is more than 50% shorter than with conventional methods. The phase that sees substantial reductions is that of the alignment and fine-tuning in particular (Charavet et al., 2021).

Digital twins are also useful for managing complex cases. Virtual simulation of treatment sequences allows clinicians to evaluate different strategies before implementation, supporting more informed decision-making. At the same time, these models can be used to visually communicate expected changes with dental and skeletal relationships, which may improve patient understanding and facilitate the informed consent process. Such capabilities are particularly valuable in interdisciplinary treatment planning, where clear communication among clinicians is essential. (Charavet et al., 2021).

3.3 Orthognathic and Surgical Planning

Digital twins have significant potential, demonstrated in oral and maxillofacial surgery, particularly orthognathic and complex craniofacial reconstruction. Digital twins improve the process of orthognathic surgery, enabling detailed planning through virtual simulations that accurately reflect skeletal positions, occlusal adjustments and predicted postoperative outcomes. Convincing alterations observed after realigning the bone can be achieved by integrating three-dimensional imaging data with virtual modeling techniques, which ultimately allow clinicians to simulate osteotomies, anticipate soft tissue responses, and improve both functional and esthetic results (Andrade et al., 2024; Li et al., 2025). These combined medical sciences have improved skeletal repositioning accuracy, reduced uncertainty during operating room procedures, and enabled realistic visualization of outcomes for patient counseling (Mahmood et al., 2024).

In complex mandibular reconstruction cases following tumor resection, digital twins are employed to preoperative planning of bone resection, guide implant placement with surgical precision, and prosthetic rehabilitation (Zaleckas et al., 2024). By having complete prosthodontic work identified in advance of surgery and implant positioning during the surgical procedure entirely verified within virtual modelling, patient outcomes will benefit greatly.

3.4 Treatment Simulation and Patient Communication

Beyond procedural planning, digital twins play an important role in treatment simulation and patient communication. By generating detailed visual representations of anticipated treatment outcomes, these systems allow patients to better understand proposed interventions and their potential effects (Cellina M et al., 2023). This enhanced visualization supports shared decision-making and strengthens the informed consent process. In addition, involving patients more actively in treatment planning may improve their motivation and adherence to treatment protocols. From a clinical perspective, the ability to compare predicted outcomes with actual results also provides valuable feedback, which can support continuous improvement in treatment planning and delivery.

4. Integration with Artificial Intelligence and Advanced Technologies

4.1 Machine Learning Applications

Artificial intelligence algorithms expand the capabilities of digital twins in multiple domains. Computer-aided systems are closely integrated with traditional methods to classify dental findings visible on panoramic radiographs by degree of severity. Distinguishing between normal anatomy, moderate pathology, and severe conditions (Iliuță et al., 2025). Furthermore, automated systems can standardize diagnoses, streamline medical protocols, and support the training of non-specialists.

Convolutional neural networks (CNNs) for dental image analysis achieve good performance in detecting tooth decay, assessing periodontal health, and screening for oral cancer. However, challenges persist, such as the lack of transparency in algorithms and integration into medical treatment practice (Bonny et al., 2024). AI in clinical workflows needs to be transparent, explaining how the algorithms work, why they are deployed, and how they meet regulatory requirements.

4.2 Integration of Multiple Technologies

The most advanced dental digital twins integrate AI, Internet of Things (IoT) sensors, and extended reality technologies to create comprehensive systems supporting clinical decision-making. Large language models now enable the creation of AI-generated digital twins by synthesizing electronic health records and other available patient data, overcoming limitations of sparse or incomplete datasets (Wang et al., 2024). This approach democratizes access to digital twins technology for settings where comprehensive 3D imaging may not be routinely available.

5. Security, Privacy, and Ethical Considerations

5.1 Data Protection and Regulatory Compliance

Establishing digital twins in dentistry presents significant challenges for patient data security and privacy. Dentistry, as a healthcare field, must comply with strict data protection regulations, such as the Health Insurance Portability and Accountability Act (HIPAA), and the General Data Protection Regulation (GDPR). Therefore, digital twins systems must include robust encryption, rigorous access controls, and an audit mechanism to guarantee data confidentiality across multiple patient data types from different cloud systems (Jameil et al., 2024).

Edge computing using advanced cybersecurity solutions offers an earnest way; protecting digital twin data requires real-time processing and proactive risk detection via predictive analytics (Jameil et al., 2024). However, the incorporation of these security measures will increase complexity and cost which may decrease their suitability for use in resource-limited areas.

5.2 Ethical Frameworks

Some of the ethical issues surrounding digital twins in dentistry are: information security, algorithmic bias, informed consent, and equal opportunities. The methodological limitations of current assessments of AI-based diagnostic models are cause for concern, given the potential dangers associated with early clinical application (Salvi et al., 2025). The working principles, the types of data they use, and their actual performance across different digital twin applications are quite opaque.

Additionally, broad access to digital twins technology is a matter of ethics for accessibility. The high costs of advanced imaging platforms, computational hardware, and software licenses make access to the technology difficult, especially in the developing world and among economically disadvantaged populations (Thiribhuvanan et al., 2025). Hence, it is imperative to investigate approaches that could democratize access, such as lightweight deployments and cloud solutions that can bridge the divide between availability and usage of these cutting-edge tools.

6. Current Limitations and Technology Gaps

6.1 Validation and Clinical Evidence

Although preliminary results are promising, significant methodological gaps remain in validating dental digital twins. Many studies have reported high performance metrics, but have failed to rigorously confirm their truth in actual clinical settings and diverse circumstances. Sample sizes are typically inadequate, control groups are often absent, and long-term clinical outcomes remain little studied.

In dentistry, digital twins and the Internet of Things are still mainly theoretical or at the pilot stage. This leap has not yet been successfully made. The gap between the potential for what might be done out there and actual practice in clinics needs to be breached. To transform promising laboratory demonstrations into successful clinical implantations, a comprehensive validation system that integrates into healthcare professionals' existing workflows and is shown to be cost-effective is required (Salvi et al., 2025).

6.2 Integration Challenges

There are many challenges for the clinical application of digital twins, especially regarding workflow integration, compatibility with existing platforms, and training demands. Most dental practices lack the technological infrastructure to support sophisticated digital twin systems. Among these barriers are limited data storage, weak cybersecurity, and lack of staff with appropriate expertise (Maddahi et al., 2022). Furthermore, the norms governing data formats, communication protocols, and system architecture are at an early formative stage, which impedes interoperability between systems from different platforms or vendors.

7. Applications in Dental Education

7.1 Remote Learning and Simulation

Digital twins have been considered a game-changer toward improving dental education, notably for distance learning. These virtual patient models allow students to improve their diagnostic and treatment planning capabilities in a controlled environment, before engaging with actual patients (Maddahi et al., 2022). Such an application was particularly needed during COVID-19, and by necessity, since education had to continue remotely.

Immersive virtual reality environments with surgical digital twins allow students to explore realistic 3D models of actual operating rooms and view treatments from numerous perspectives (Hein et al., 2024). These immersive experiences lead to vastly improved learning compared to traditional two-dimensional (2D) videos or text descriptions and allow learners to understand complex spatial relationships more effectively.

7.2 Competency Assessment

Digital twins technology enables an unbiased assessment of procedural competency by tracking metrics such as performance during simulated procedures. By quantifying deviations from predicted virtual results, this technique provides quantitative feedback on procedural accuracy. Such feedback may help reduce the learning curve and improve clinical outcomes when students transfer to treating real patients.

8. Future Directions and Emerging Applications

8.1 Advanced Multimodal Integration

Dental digital twins of the future may be enabled to incorporate additional data types, such as genomic information, microbiome profiles, and real-time metabolic output from wearable sensors. This integration of diverse

patient-level information will enable the development of truly personalized treatment plans, tailored to a given patient's specific characteristics and estimated responses to interventions (Thiribhuvanan et al., 2025).

8.2 Blockchain and Secure Data Sharing

As part of a digital twins, the blockchain mechanism that accompanies it, facilitating secure and transparent sharing of healthcare information among care providers, in such a manner that patient privacy can be ensured, all the while maintaining integrity (Moztarzadeh et al., 2023). Through the utilization of decentralized architectures, this approach could potentially foster higher interest among users, as it reduces dependence on centralized cloud hosts while simultaneously reducing the effect of related cybersecurity challenges.

8.3 Precision Medicine in Dentistry

Digital twins represent a key technology enabling precision dentistry through patient-specific simulation, predictive modeling of treatment response, and optimization of interventions based on individual characteristics (Cellina M et al., 2023; Papachristou et al., 2024). This paradigm shift from population-based to patient-centered approaches has the potential to substantially improve clinical outcomes and patient satisfaction.

9. Challenges and Barriers to Implementation

9.1 Technical and Infrastructural Challenges

The adoption of dental digital twins requires extensive investment in imaging devices, computational resources, and software development. Several barriers hinder the adoption of digital twins within existing practice management systems in dentistry, which are attributed to the absence of standards and interoperability. Moreover, users are another major obstacle to overcome, as practitioners need training, since optimal use of the digital twin as a technology requires not only general application knowledge but also technical expertise (Xames et al., 2024).

9.2 Regulatory and Reimbursement Issues

The regulatory landscape for digital twin systems is underdeveloped, with uncertainty around pathways to approval or mechanisms for clinical validation. Moreover, the compensation for services associated with digital twin technology is currently extremely limited across most insurance plans, which undermines financial incentives for their use in fee-for-service settings (Xames et al., 2024).

Conclusion and suggestions

Digital twins are increasingly applied across multiple areas of dentistry, including implantology, orthodontics, and surgical planning, supported by advances in imaging and AI technologies. However, current evidence remains inconsistent, partly due to variations in definitions and implementation, which limit comparability and scalability. While the strongest clinical support exists for guided implant surgery, other applications remain largely based on preliminary studies. In addition, concerns related to algorithm reliability, data security, and regulatory uncertainty remain insufficiently addressed. Overall, a more cautious, evidence-based approach supported by robust clinical studies and standardized methodologies is needed before wider clinical adoption can be achieved.

The concept of digital twins is a disruptive innovation with the potential to transform dental practice, research, and training. Tested applications show promising results, especially in treatment planning, surgery assistance and

patient communication. However, there remain significant differences between what we can currently do and the promise of this technology.

The next steps require interdisciplinary work among clinicians, engineers, computer scientists, and ethicists to address the complex technical, clinical, and ethical challenges ahead. Before integrating these innovations into routine clinical practice, rigorous clinical validation through large, prospective, randomized trials is necessary. Standardization of protocols, as well as encumbrance-free training, are essential for successful adoption. It is also critical for discussions around equitable access, data privacy and ethical stewardship to develop alongside technologies as digital twins must help rather than hinder all populations and should not widen existing health inequities.

When combined with artificial intelligence (AI), the Internet of Things (IoT), and extended reality (XR) technologies, digital twins enable new opportunities for precision dentistry tailored to individual patient needs. Bringing this potential to fruition is contingent on continuous innovation, rigorous validation, and responsible deployment of applied principles that ensure the focus on patient benefit and data security as well as equitable access.

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Author Contributions

The author solely carried out all contributions in accordance with the CRediT taxonomy. This includes conceptualization, development of the methodology for the literature search and synthesis, data curation, critical evaluation and analysis of the reviewed literature, and writing the manuscript, including both the original draft and subsequent review and editing.

Conflict of Interests

The author declares no conflict of interest.

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Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the author used Grammarly for English language editing and grammar correction. Following its use, the author thoroughly reviewed and edited the content and accept full responsibility for the final version of the publication.

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