

Digital Dentistry & Material Science: Sculpting the Future of Oral Care- A Narrative Review

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Abstract: This review examines the dynamic intersection of digital dentistry and material science, exploring current trends and advancements shaping modern dental practice. The integration of digital technologies, including intraoral scanners, cone-beam computed tomography (CBCT), and computer-aided design/computer-aided manufacturing (CAD/CAM) systems, has revolutionized diagnostic and restorative workflows. Concurrently, material science innovations, particularly in ceramics, composites, and 3D printing resins, are expanding the possibilities for dental restorations and prostheses. This review analyzes the accuracy, efficiency, and clinical outcomes associated with these technologies and materials, emphasizing the impact on patient care. It further explores the integration of digital workflows, including virtual treatment planning and teledentistry, and discusses the role of emerging technologies like artificial intelligence (AI), VR in future dental applications. By synthesizing current research and clinical evidence, this review provides a comprehensive overview of the evolving landscape of digital dentistry and material science, highlighting the potential for enhanced precision, predictability, and patient satisfaction in dental treatments, while also addressing current limitations and future directions.

Keywords: Digital Dentistry, Dental Materials, CAD CAM, CBCT, VR.

1. Introduction

The field of dentistry is undergoing a profound transformation, driven by the convergence of digital technology and advancements in material science. Traditionally, dental procedures relied heavily on manual techniques, subjective assessments, and materials with inherent limitations, resulting in variability and potential inaccuracies. Digital dentistry, however, offers a paradigm shift, enabling increased precision, efficiency, and patient comfort through technologies like intraoral scanners and CAD/CAM systems[1,2]. Concurrently, material science has evolved to produce biocompatible, mechanically robust, and aesthetically pleasing materials, crucial for the success and longevity of dental restorations[3,4]. The synergy between digital design and manufacturing, and the development of these advanced materials, is leading to more predictable and customized patient treatments. Dentistry is rapidly transitioning to digital technology, with advancements in intraoral scanners, digital radiography, CAD/CAM, 3D printers, and AI software, VR revolutionizing the field. Digital dentistry offers precision and accuracy, with digital imaging technologies like CBCT and radiography providing detailed images for treatment planning[5]. It also allows for faster restorations, with CAD/CAM technology allowing for single-session design and creation. Digital dentures offer increased precision, quicker production times, and more personalized options, making them more eco-friendly and less painful[6,7].

This review aims to explore this dynamic intersection, clearly defining the boundaries of digital dentistry and relevant material science areas, including specific imaging modalities, CAD/CAM systems, and material classes. The objectives are to analyze current trends, evaluate the accuracy and reliability of

digital technologies, assess the properties and clinical performance of advanced dental materials, identify emerging trends, and examine the impact on clinical workflows and patient outcomes. Following this introduction, the review will delve into digital imaging, CAD/CAM applications, advancements in dental materials, clinical applications, and future trends, providing a comprehensive overview of the evolving landscape.

2. Digital Imaging and Data Acquisition

The realm of digital imaging and data acquisition has fundamentally reshaped dental practice, offering unprecedented levels of precision and efficiency. Intraoral scanners, at the forefront of this revolution, have undergone significant technological advancements, with improvements in optical, laser, and confocal technologies[8,9]. These advancements, coupled with sophisticated software algorithms, have enhanced the accuracy and precision of digital impressions, crucial for achieving optimal clinical outcomes. The clinical applications of intraoral scanners are diverse, spanning restorative dentistry, orthodontics, implantology, and prosthodontics. Notably, they minimize patient discomfort, streamline workflows, and facilitate seamless communication between clinicians and laboratories. However, the market offers a variety of scanner technologies, each with unique characteristics. Therefore, a comparative analysis of these technologies, considering factors such as accuracy, speed, ease of use, and cost, is essential[10,11]. Complementing intraoral scanners, cone-beam computed tomography (CBCT) has emerged as an indispensable tool for diagnosis, treatment planning, and surgical guidance. CBCT's ability to generate detailed 3D reconstructions of oral and maxillofacial structures has revolutionized implant planning, endodontics, orthodontics, and oral surgery. Furthermore, advancements in CBCT technology have focused on enhancing image resolution while minimizing radiation exposure, adhering to the ALARA principle[3,6,12].

Digital radiography has also played a crucial role in improving diagnostic capabilities. Compared to traditional film-based radiography, digital radiography offers instant image acquisition, reduced radiation exposure, and enhanced image quality through advanced sensor technology and software processing. The integration of digital radiographs with electronic health records and other digital data, such as intraoral scans and CBCT images, facilitates comprehensive treatment planning. Moreover, artificial intelligence is increasingly being integrated into digital radiography, enhancing the ability to detect and diagnose dental pathologies[10,13,14].

CAD/CAM Technology and Digital Workflows

The integration of Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology has revolutionized dental workflows, enabling the precise design and fabrication of dental restorations and appliances. Computer-Aided Design (CAD) software has undergone significant advancements, offering clinicians and technicians intuitive tools for designing crowns, bridges, veneers, and other restorations with exceptional accuracy[9,11,15]. These advancements include sophisticated algorithms for anatomical modeling, virtual articulation, and aesthetic considerations, allowing for highly customized and predictable outcomes. Furthermore, CAD software plays a pivotal role in the digital design of surgical guides for implant placement and orthodontic appliances, facilitating minimally invasive procedures and optimized treatment planning.

Complementing CAD, Computer-Aided Manufacturing (CAM) technologies, such as milling and 3D printing, translate digital designs into physical restorations. Milling technologies, utilizing a variety of materials including ceramics, composites, and metals, offer high precision and surface quality, crucial for achieving optimal fit and function. 3D printing, an additive manufacturing process, expands the possibilities for dental applications, enabling the fabrication of surgical guides, dental models, orthodontic appliances, and even provisional and definitive prostheses from a range of materials, including resins, polymers, and metals[3,7,9]. The selection of materials and manufacturing techniques is critical, influencing the mechanical properties, biocompatibility, and aesthetics of the final restoration[15,16].

The seamless integration of these CAD/CAM technologies into digital workflows enhances communication and collaboration between clinicians and laboratories. Digital treatment planning, facilitated by virtual simulations, allows for the visualization of treatment outcomes and the optimization of restorative designs before fabrication. This digital communication streamlines the exchange of information, minimizing errors and reducing turnaround times. Additionally, the emergence of teledentistry applications further extends the reach of digital workflows, enabling remote consultations,

treatment planning, and monitoring, ultimately improving access to care and patient convenience[10,17].

Advancements in Dental Materials

Advancements in dental materials are integral to the success of digital dentistry, offering a wide range of options to meet diverse clinical needs. Dental ceramics, particularly zirconia and lithium disilicate, have gained prominence due to their exceptional strength and biocompatibility. Recent developments have focused on enhancing their translucency and aesthetics, enabling the creation of highly natural-looking restorations. Zirconia, known for its high fracture resistance, is now available in more translucent forms, while lithium disilicate offers excellent aesthetics and can be fabricated using both CAD/CAM and pressing techniques. Other high-strength ceramics are also being explored, expanding the material choices for clinicians[18,19].

Composite materials, another cornerstone of restorative dentistry, have seen significant improvements with the advent of nanocomposites and bulk-fill composites. Nanocomposites, incorporating nanoparticles, offer enhanced mechanical properties, such as increased strength and wear resistance, while maintaining excellent aesthetics. Bulk-fill composites simplify the restorative process by allowing for larger increments of material to be placed, reducing chair time and improving handling characteristics. These advancements have improved the longevity and predictability of composite restorations[12,16,20].

The rise of 3D printing in dentistry has spurred the development of specialized printing materials, including resins, polymers, and metals. Resins and polymers, used for fabricating surgical guides, dental models, and provisional prostheses, are being engineered for improved biocompatibility and mechanical properties. Metals, such as titanium and cobalt-chromium alloys, are being explored for 3D printing of implant frameworks and other metal-based restorations. The ongoing research ensures the printed material suits the requirements of intraoral applications[19,21].

Biomaterials play a critical role in implant dentistry and regenerative procedures. Implant materials, primarily titanium and its alloys, are selected for their osseointegration properties and biocompatibility. Bone grafting materials, including allografts, xenografts, and synthetic bone substitutes, are used to augment bone deficiencies and promote bone regeneration. Regenerative materials, such as growth factors and tissue-engineered constructs, are being explored to enhance tissue healing and regeneration[20,22].

Nanotechnology is revolutionizing dental materials by enabling the creation of materials with tailored properties at the nanoscale. Nanoparticles are being incorporated into composites, adhesives, and bone grafting materials to enhance their mechanical strength, antibacterial properties, and biocompatibility. Nanocoatings are also being developed to improve the surface properties of dental implants and restorations, promoting osseointegration and reducing bacterial adhesion. These advancements in nanotechnology hold immense potential for improving the performance and longevity of dental materials[23,24].

Clinical Applications and Outcomes

The integration of digital technologies and advanced materials has significantly impacted clinical applications and patient outcomes across various dental specialties. In restorative dentistry, digital workflows, encompassing intraoral scanning, CAD/CAM design, and fabrication, have revolutionized the creation of crowns, bridges, and veneers. These workflows enhance precision, reduce chairside time, and improve patient comfort. The accuracy of digital restorations, particularly in terms of marginal fit and occlusal harmony, is a critical factor influencing their longevity. Clinical studies have demonstrated the comparable, and in some cases superior, accuracy of digitally fabricated restorations compared to traditional methods, leading to improved patient satisfaction and long-term success[6,9,16].

A study by Arslan M[25] Concluded that The Flexural Strength and hydrophobicity of the CAD/CAM PMMA-based polymers were higher than the conventional heat-polymerized PMMA, whereas the CAD/CAM PMMA-based polymers had similar Ra values to the conventional PMMA. Thermocycling had a significant effect on FS and hydrophobicity except for the Ra of denture base materials. A study by Steinmassl O et al [26] tested the hypothesis that CAD/CAM dentures have higher denture base congruence than conventional dentures due to the reduction of resin polymerisation shrinkage. CAD/CAM dentures from four manufacturers showed lower mean incongruences compared to conventional dentures. AvaDent Digital Dentures had the highest congruence with the master cast surface, while Wieland Digital Dentures had the lowest. The study concluded that CAD/CAM produces dentures with better fit and enhanced retention, which could explain the lower traumatic ulcer-frequency

observed in CAD/CAM dentures. Charoenphol K et al[27] compared the fit accuracy of milled and 3D-printed complete denture bases. The results showed that milled denture bases were more accurate in adaptation in the overall intaglio area and primary bearing area, while 3D-printed dentures showed greater accuracy in the peripheral/posterior palatal seal area. Milled denture bases fit better in overall and primary stress-bearing areas, while 3D-printed dentures appeared more accurate in the peripheral seal area due to a minor undercut. Lo Russo L et al [28] aimed to compare the trueness of the intaglio surface of milled and 3D-printed removable complete digital dentures. Intraoral scans were obtained from 14 participants for 20 edentulous arches, and ten maxillary and 10 mandibular denture bases were designed and fabricated using a digital workflow. Standard tessellation language (STL) files of the printed and milled denture bases were used for 3D analysis. The results showed that milling provided a global better trueness of the entire intaglio surface than 3D-printing, with less variation across several zones of interest. However, the magnitude of these differences may be of limited clinical significance. The study suggests that milling can provide a slightly better trueness of the intaglio surface within the limits of manufacturing methodologies used for complete dentures.

In implant dentistry, digital implant planning and the utilization of surgical guides have enhanced the predictability and safety of implant placement. Digital planning, based on CBCT data and intraoral scans, allows for precise implant positioning, minimizing the risk of complications and optimizing prosthetic outcomes. Material selection for implant prostheses is crucial, with zirconia and titanium alloys being favored for their biocompatibility and mechanical strength. Digital workflows facilitate the fabrication of customized implant abutments and prostheses, ensuring optimal fit and aesthetics[5,17,19,20].

Orthodontics has also benefited significantly from digital advancements. Digital fabrication of aligners and appliances, based on intraoral scans and CAD/CAM technology, enables the creation of highly customized orthodontic devices. Virtual treatment planning and monitoring, facilitated by 3D imaging and software simulations, allow for precise control of tooth movement and improved treatment efficiency. This digital approach enhances patient comfort, reduces treatment time, and improves the overall orthodontic experience[20,29,30].

Surgical applications of digital technology extend beyond implant placement. Digital surgical guides, fabricated using CBCT data and CAD/CAM technology, are utilized in various oral surgery procedures, including guided bone regeneration, periodontal surgery, and maxillofacial surgery. These guides enhance surgical precision, minimize invasiveness, and improve patient outcomes. Additionally, the use of 3D printing in surgical planning allows for the creation of patient-specific anatomical models, aiding in pre-surgical visualization and improving surgical accuracy[21,24,31].

Digitalization in oral health care is transforming the treatment process, with new devices and software being used to automate patient quality assessments and monitor treatment progress. This allows clinicians to recognize their success from patients' perspectives, leading to value-based oral health care. Telemedicine infrastructure is also accelerating the exchange of medical data, reducing information loss and unnecessary duplication of testing. Continuous monitoring of treatment progress through patients' activity allows for direct communication with the orthodontist, reducing visits and improving oral hygiene[16,18,32].

Digital manufacturing processes have shown promise in improving patient outcomes, such as faster and more accurate treatment decisions. However, there is limited evidence that digital manufacturing is superior to conventional methods in terms of patient OHRQoL. Digital impressions are a viable alternative to traditional protocols for implant-supported crowns and implant-retained full-arch immediate loading prostheses[25,33,34].

Multiple in vitro studies reported insufficient accuracy of intraoral scanners (IOSs) for complete-arch multiple implant impression. Orejas-Perez J, et al analysed[33] the precision of three IOSs, PIC dental (Pic dental, Iditec North West SL), TRIOS 3 (3Shape), and True Definition (Midmark Corporation) and the influence of several factors in the edentulous complete maxillary and mandibular arch. A fully edentulous patient with eight implants was selected and five impressions were taken per system and arch. Significant differences were observed in distances and angulations. The PIC system had the best precision, followed by TD and T. The type of arch did not affect PIC precision.

Computer-aided manufacturing has made millable, printable, and laser sinterable materials available for dental purposes, improving fit and esthetics. However, most patients still prefer conventional dentures over 3D-printed dentures. Digital data storage allows for one-way delivery in long-distance transport, saving time in restoring impaired OHRQoL[25,35,36].

Virtual facebow and jaw movement recording data assists in simulating vertical changes in the jaw relationship in dental laboratories. Three-dimensional facial scan data is enabling better esthetic simulation of maxillofacial surgery, surgical prosthetic and epithetic outcomes, and orthodontic procedures. Cone beam computed tomography is used for various clinical indications, including resorption, preoperative assessment of surgical and non-surgical endodontic retreatment, location of missing canals, and differential diagnosis[27,29,36].

3. Future Trends and Challenges

The future of digital dentistry and material science is poised for transformative advancements, albeit with certain challenges. Artificial intelligence (AI) is rapidly emerging as a key driver of innovation, with potential applications in AI-driven diagnostics and treatment planning. AI algorithms can analyze vast datasets of patient images and clinical information to assist clinicians in detecting dental pathologies, predicting treatment outcomes, and developing personalized treatment plans. Furthermore, the integration of robotics into dental procedures holds promise for enhanced precision and minimally invasive interventions. Robotic systems, guided by AI, could perform complex surgical tasks with greater accuracy and consistency than human operators. However, the widespread adoption of AI and robotics requires rigorous validation, regulatory frameworks, and ethical considerations[17,19,28,30]. Advancements in material science are also shaping the future of dentistry. The development of new biomaterials and nanocomposites with enhanced mechanical properties, biocompatibility, and aesthetic qualities is crucial for improving the longevity and performance of dental restorations. Personalized dental materials, tailored to individual patient needs, are also being explored, leveraging genetic information and other patient-specific data. This approach could lead to more predictable and successful treatment outcomes[31,34,37].

Despite the promising potential of these advancements, several challenges and limitations must be addressed. The high cost of digital technologies and advanced materials can create barriers to access for both clinicians and patients. Standardized protocols and comprehensive training programs are essential for ensuring the effective and safe implementation of these technologies[38,39]. Additionally, long-term clinical studies are needed to evaluate the performance and durability of digital materials and restorations over time. These studies should focus on assessing factors such as biocompatibility, wear resistance, and long-term aesthetic stability. It has also revolutionized dental education by integrating digital resources like simulation software and virtual reality, improving patient knowledge and communication, and offering precise, effective treatments. However, not all dental procedures can be fully replaced by digital technologies. Digital dentistry also has the potential to reduce waste, energy consumption, and chemical usage, contributing to environmental preservation[7,10,40,41]. Advantages, clinical applications and future trends of digital dentistry and Material science demonstrated in (Table 1). Despite these challenges, digital dentistry has the potential to revolutionize dental education and improve patient outcomes. Overcoming these challenges is crucial for realizing the full potential of digital dentistry and material science in improving patient care

Table 1 Digital Dentistry and Material Science

Category	Technology/Material	Key Features/Advantages	Clinical Applications	Future Trends/Challenges
Digital Imaging	Intraoral Scanners	High accuracy, digital impressions. Improved patient comfort. Efficient workflow.	Restorative dentistry, Orthodontics, Implantology.	Enhanced scanning speed and accuracy. AI-driven image analysis. Cost of equipment.
Digital Imaging	CBCT	3D imaging for detailed diagnostics. Precise surgical planning. Reduced radiation options.	Implant planning, Oral surgery, Endodontics.	Lower radiation doses. Integration with AI for diagnosis.
CAD/CAM	CAD Software	Precise design of restorations. Virtual treatment planning. Customized appliance design.	Crowns, bridges, veneers. Surgical guides. Orthodontic appliances.	AI-driven design optimization. Improved software integration.
CAD/CAM	CAM (Milling/3D Printing)	Precise fabrication of restorations. Variety of material options. Efficient production.	Restorations, models, guides. Prostheses. Orthodontic appliances.	Advanced material compatibility. Increased speed and precision. 3D printing with metals.

Dental Materials	Dental Ceramics (Zirconia, Lithium Disilicate)	High strength and durability. Excellent aesthetics. Biocompatibility.	Crowns, bridges, veneers. Implant abutments.	Improved translucency and color matching. Enhanced processing techniques.
Dental Materials	Composite Materials (Nanocomposites)	Improved mechanical properties. Good aesthetics. Versatile applications.	Direct and indirect restorations. Cosmetic dentistry.	Enhanced wear resistance. Improved handling properties.
Dental Materials	3D Printing Resins/Metals	Customized fabrication. Variety of material properties. Rapid prototyping.	Surgical guides, Provisional prostheses. Dental frameworks.	Improved biocompatibility. Increased material strength.
AI	Digital Implantology	Precise Implant placement. Surgical guide usage. Improved prosthetic outcomes.	Implant placement surgery. Prosthetic restoration.	Robotic assisted implant surgery. Improved bone integration materials.
AI	Artificial Intelligence	Cost of technology. Need for training. Long term material research.	All dental fields.	Standardization of digital workflows. Ethical concerns regarding AI.

VIRTUAL REALITY IN DENTISTRY

Virtual reality (VR) is emerging as a powerful tool within dentistry, demonstrating significant potential in both patient care and professional training. Studies consistently highlight VR's efficacy in reducing patient anxiety and pain during various dental procedures, from implant surgeries to routine treatments. This is achieved by immersing patients in calming virtual environments, effectively diverting their attention from the stressful aspects of dental work. Furthermore, VR is proving invaluable in dental education, offering realistic simulations for training in surgical decision-making and radiography. These simulations allow students to practice complex procedures in a safe, controlled environment, enhancing their skills and knowledge. The overall trend signifies that VR is not just a novelty in dentistry, but a transformative technology that can improve patient experiences and elevate the standard of dental education[42-49].(TABLE 2)

TABLE 2 VIRTUAL REALITY IN DENTISTRY

Study	Authors (Year)	Study Design	Participants	Intervention	Primary Outcomes	Key Findings
1	Tanja-Dijkstra et al.[42]. (2014)	Randomized Controlled Trial	Patients (18+) undergoing fillings or extractions (max 30 mins)	VR (natural environment), VR (urban environment), Standard care (control)	Memories of treatment (pain, intrusive thoughts, vividness), Dental experience, Treatment experience, VR experience	Protocol: To determine if VR improves dental experience and memories, especially for high-anxiety patients. To test if natural vs. urban VR environments differ.
2	Tanja-Dijkstra et al. (2014) [43]	Simulation Study	69 participants (simulated dental experience)	VR (active), VR (passive), Control	Memories of treatment (vividness), Perceived control	VR distraction affected memories (vividness) a week later. High-anxiety participants showed greater reduction in memory vividness.
3	Sweta et al.[44] (2019)	Randomized Controlled Trial	50 patients undergoing local anesthesia administration	VR during anesthesia, No VR (control)	Pulse rate, Oxygen saturation, Pain (Visual Analog Scale)	VR significantly reduced pain perception and altered physiological responses (oxygen saturation, pulse rate).
4	Custódio et al.[45] (2020) (Review)	Meta-analysis of Randomized Clinical Trials	Children (up to 12 years) undergoing dental treatment	VR glasses for audiovisual distraction	Dental anxiety, Pain perception, Behavior	VR glasses improved behavior and reduced pain perception during caries removal and restoration. No significant differences in anxiety during local anesthesia or rubber dam use.
5	Al Kheraif et al.[46] (2024)	Cross-sectional study	140 children and adolescents with Autism	VR (natural environment) during dental examination,	Anxiety (Venham scale), Cooperation	VR significantly reduced anxiety and increased cooperation in children with

			Spectrum Disorder (ASD)	Conventional dental examination (control)	(Frankl behavior rating scale)	ASD during dental examinations.
6	Ghobadi et al.[47] (2024)	Randomized Controlled Trial	73 patients undergoing dental implant surgery	VR during one surgery, no VR during another	Anxiety (State-Trait Anxiety Inventory, Modified Dental Anxiety Scale), Pain (Numerical Rating Scales), Patient Satisfaction, Surgeon Distress, Memory Vividness, Time Perception, Physiological data (biofeedback, neurofeedback)	VR significantly reduced anxiety and pain. Increased patient satisfaction. Reduced time perception and memory vividness.
7	Vannaprathip et al[48]. (2025)	Randomized Controlled Trial	Dental students undergoing root canal treatment training	SDMentor (VR with intelligent tutoring), standard training (control group)	Situation awareness, procedural knowledge, overall performance	SDMentor significantly improved learning outcomes compared to standard training.
8	Im JE et al.[49] (2025)	Randomized Controlled Trial	79 participants	3DOVR-DR(experimental group), Google Cardboard VR(control group)	User Experience of VR training	3DOVR-DR tool provided an immersive learning experience, with significantly higher user experience ratings compared to Google Cardboard VR.

4. Conclusion

Digital dentistry and material science have transformed oral healthcare. Key advancements in imaging, CAD/CAM, and materials enhance precision and efficiency. Digital workflows improve patient care and satisfaction. Future trends like AI, VR and personalized materials promise further advancements, but challenges in cost, standardization, and long-term performance must be addressed for widespread adoption.

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