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Advances in digital dentistry: Impact of different technologies

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***Abstract*---Background:** Digital technologies have revolutionized various fields, and dentistry is no exception. The integration of advanced digital systems into dental practice has significantly transformed clinical workflows and patient care. This review explores the impact of different digital technologies on dentistry, emphasizing the progress and current state of digital systems. **Aim:** The aim of this review is to examine the advancements in digital dentistry, focusing

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on key technologies such as CAD/CAM systems, imaging technologies, and practice management software, and their implications for clinical practice and material science. **Methods:** The review synthesizes information from a range of sources, including historical developments and current technological innovations in digital dentistry. Key areas of focus include intraoral and laboratory scanners, CAD/CAM systems, additive manufacturing, and workflow optimization. **Results:** Digital systems have significantly improved the accuracy and efficiency of dental restorations and treatments. Intraoral scanners provide real-time imaging and detailed digital visuals, enhancing patient communication and comfort. CAD/CAM systems have expanded to accommodate a wide range of dental appliances and restorations. Additive manufacturing, or 3D printing, has introduced new materials and design possibilities, contributing to the development of complex dental prostheses and models. The advent of open architecture systems has further streamlined workflows, while digital patients and computer-assisted surgery have enhanced precision in treatment planning and execution. **Conclusion:** The integration of digital technologies into dentistry has led to substantial advancements in clinical practice. Modern digital systems offer improved accuracy, efficiency, and patient satisfaction, with ongoing innovations continuing to shape the future of dental care. The continued development of these technologies promises further enhancements in restorative procedures, material science, and personalized treatment planning.

***Keywords*---**Digital Dentistry, CAD/CAM Systems, Intraoral Scanners, Additive Manufacturing, Workflow Optimization, Computer-Assisted Surgery, Digital Patient

Introduction

Digital systems are now pervasive in our daily lives. The interconnectivity rate has soared by 1125% since the year 2000. By June 2019, 57.3% of the global population owned a cell phone, with ownership rates exceeding 80% in Europe and North America (1). Digital assistants respond to voice commands, performing tasks such as answering queries, ordering food, arranging transportation, translating spoken languages, and comparing product brands (2). Beds can automatically adjust your position if snoring is detected (3). Sensors in baby diapers monitor activities and notify caregivers when a change is needed (4). Almost every home device, from window blinds to pet feeders, can be digitally controlled via buttons or voice commands (5). Therefore, it is no surprise that digital systems are increasingly becoming integrated into the field of dentistry.

Pioneers in Digital Dentistry

Historically, digital advancements have been primarily focused on three areas: CAD/CAM systems, imaging technologies, and practice/patient management systems. CEREC™, the first commercially available in-office CAD/CAM system, enabled the production of same-day restorations (6). Around the same time, Procera™, a laboratory-based system, was introduced (7). These innovations spurred the evolution of new materials (8) and the development of numerous other CAD/CAM systems (9). Early advancements in imaging included both intraoral imaging systems integral to the CEREC™ system and developments in digital radiography. Introduced in the late 1980s, digital radiography revolutionized the field by enhancing image quality and evolving from phosphor plates to solid-state detectors, cone beam computed tomography (CBCT), and new generations of intraoral scanners (10).

Practice management software facilitated the collection of patient demographics, scheduling, interactions with insurance companies, billing, and report generation. Simultaneously, electronic patient records—digital versions of patient-centered, clinically-oriented information—prompted improvements in tracking patient health, assessing quality of care, and mining data for research, including evaluating the efficiency and effectiveness of clinical procedures (11). Simultaneously, other technologies have significantly influenced and enabled innovations in digital dentistry, often at an astonishing pace. Although not exhaustive, these technologies include sensor miniaturization, artificial intelligence, augmented and virtual reality, robotics, 3D printing, telehealth, big data, interoperability, the Internet of Things, nanotechnology, quantum computing, biomedical engineering, data storage costs, connectivity, and more. Many of these technologies were unimaginable two decades ago, with terms that were not even known then.

The Current and Future State of Digital Dentistry

Undeniably, the field of dentistry is undergoing a transformation. To varying degrees, digital systems are now integral to nearly every aspect of dentistry. Modern systems are user-friendly, patient-friendly, versatile, and valuable clinical tools (12). While the range of digital systems is vast, this discussion primarily focuses on those with significant implications and opportunities for material science advancements and innovations.

Scanners: Contemporary scanners, whether intraoral or laboratory-based, have revolutionized restorative dentistry. Real-time imaging now provides on-screen digital visuals of single or multiple teeth, full arches, opposing arches, occlusion, and surrounding soft tissues.

Intraoral Scanners: On-screen images simplify the explanation of treatment options to patients, who also appreciate the more comfortable data acquisition process. Bulky plaster casts/models are replaced by easily stored digital files that can be retrieved for various purposes at any time. Based on comprehensive data from the 11 intraoral scanners showcased at the 2017 International Dental Show and updated information from suppliers, the following scanner features are summarized (13-27):

- Time required to scan a full arch: 1–10 minutes (most within 1–3 minutes)
- Tooth coating required: not needed for 8 out of 11 scanners
- Ability to capture occlusion: all systems

- Color image capture: 4 out of 11 capture in color; 7 capture only in black and white
- Shade selection enabled: possible with 3 out of 11; 6 include color image capture
- Scanner wand weight: 2.5–17.6 ounces; 6 out of 11 are under 10 ounces
- Scanner dimensions: 0.4–2.9 square inches in tip area; 8–10-inch length
- Depth of field: direct contact to 15–18 mm; one scanner ranges from 7 to 22 mm
- System configuration: available in carts, portable (hand-held/tablet), integrated into the dental chair; multiple configurations offered by most manufacturers
- Wireless connection: available in most systems
- Open/closed architecture: all systems have open architecture; 2 also offer closed architecture

Accuracy and trueness between scanned data and reference data have been extensively studied. Results indicate minor differences between intraoral scanned data, extraoral scan data, and data from conventional impressions/models, though all fall within acceptable clinical limits (28-31). Predictably, factors such as sharp corners, powder coating, and long cross-arch spans can influence accuracy (32). The scan pattern might also affect accuracy (33) or not, depending on the study design and the scanners used (34). The primary concern is whether restorations based on intraoral scan data are equivalent to those produced from conventional impressions. Most studies found no significant differences in margin fit between restorations produced by these two data acquisition methods (35-43). The precision of internal fit for conventionally and digitally imaged cross-arch prostheses was slightly inferior in digitally produced versions but still within clinically acceptable ranges (44). At least one study reported better marginal fit with digital scans, although the differences were within conventional limits (45). Digitally fabricated 3-unit ceramic frameworks fit better than conventionally fabricated metal frameworks (46). Comparing results across different studies is challenging. Between April and July 2017, 2093 publications appeared in peer-reviewed and non-peer-reviewed sources. Of these, 183 had full texts, and only 34 contained sufficient detail for in-depth analysis of digital technologies' accuracy in scanning facial, skeletal, and intraoral tissues (47). Establishing testing and evaluation standards, or at least reaching an agreement among major institutions, is necessary.

Laboratory Scanners: Currently, over 20 laboratory-based scanners are available, capable of scanning either stone casts or impressions. All offer accuracies of at least 15 µm and are widely used in office-laboratory workflows (48-52).

CAD/CAM Systems

CAD/CAM systems have transformed the design and fabrication of restorations, models, and other dental appliances. Early systems were limited to creating only inlays, but now there appears to be no boundary to the types of restorations that can be produced, ranging from simple inlays to digitally designed and fabricated full dentures, orthodontic appliances, study models, implant-related components, and both straightforward and intricate surgical guides (9). The introduction of open architecture has redefined data flow from design to fabrication, creating innovative pathways (discussed below). In 2019, there were 252 CAD/CAM-related exhibitors at the IDS meeting (53), highlighting the extensive range of CAD/CAM systems. Therefore, this discussion will focus on design innovation and the shift from subtractive to additive manufacturing.

CAD/Design Software Enhancements

The integration of data from multiple sources, combined with advanced user interfaces and CAD software capabilities, has introduced significant new possibilities. Modern software modules now feature robust aesthetic enhancements, including smile design, tooth form libraries, color matching, and tooth placement for dentures. Other advancements incorporate jaw tracking to improve and automate aspects of dynamic occlusion (9). Digital smile design combines digital facial photographs with software analysis to help practitioners and laboratory technicians create and plan treatments, providing a virtual simulation of final aesthetic results. This approach is particularly beneficial for complex, multidisciplinary restorations, facilitating communication between clinicians and laboratories, and engaging patients in aesthetic decisions and setting realistic treatment expectations (54-58). Interestingly, some studies suggest that general-purpose image-processing software, not integrated into CAD packages, can offer similar or even more comprehensive smile analysis (59, 60).

Tooth form libraries provide general tooth shapes and proportions, allowing for partial automation of restoration design and speeding up digital 'waxing' (61). Both tooth form and color are crucial for patient satisfaction. Digital photographs can be calibrated for color and white balance, then applied to virtual images obtained from intraoral scans (62, 63). Virtual tooth models with detailed color information facilitate shade matching and support collaborative decision-making between patients and clinicians regarding final restorations (62). While intraoral scans in color may potentially eliminate the need for photographic data integration, this has yet to be widely documented. It remains uncertain whether CAD software can automatically adjust for shade variations due to manufacturing processes, cement choices, or underlying tooth structure. Occlusion is a key factor in restoration design, longevity, and patient satisfaction. Jaw dynamics captured by cone beam computed tomography (CBCT) or intraoral scanners create a virtual articulator (64, 65). Data capturing the full range of static and dynamic jaw movements and occlusion can be integrated with smile design, computer-assisted implant planning, and digital maxillofacial surgery planning (65). However, the integration of data from various sources is not yet fully seamless, often requiring interactive file transfers and user interactions for superimpositions (65).

Additive Manufacturing

Additive manufacturing, commonly known as 3D printing (3DP), has become a fully integrated option in CAM hardware, providing an alternative to subtractive machining (milling). The distinct advantage of additive manufacturing is its design flexibility. Unlike traditional methods that start with a solid block, additive manufacturing builds products layer by layer, allowing for complex geometric configurations. This capability has not yet been fully exploited in the design of dental prostheses (66).

Seven different 3DP technologies are available (67-70), but four are most commonly used in dentistry: stereolithography (SLA), digital light processing (DLP), material jetting (MJ), and material extrusion (MD), with others also being explored (69, 71, 72). Invisalign™ was one of the pioneers in using 3DP to produce models with successive tooth positions for orthodontic aligners (73). Today, 3DP can create a wide range of dental components, including simple models, wax forms, tooth-colored temporaries, surgical guides, and complex long-term metal and ceramic prostheses, as well as digitally manufactured full dentures (9, 74). Materials available for 3DP include glass ceramics, cobalt chromium, composites, PMMA, resins/polymers, wax, titanium, and zirconia, with new materials continually emerging (9, 71). The quality of 3DP products is at least comparable to those made using conventional methods (75, 76). Specific studies have shown that 3DP interim crowns fit better (75, 76), drill guides are accurate within 0.25° of planned implants (77), and occlusal splints exhibit comparable polished surfaces and wear (78). The accuracy of external surfaces, intaglio surfaces, marginal areas, and occlusal surfaces of 3D-printed zirconia crowns is reported to be comparable to milled crowns (79). Custom-made templates and craniofacial prostheses produced via 3DP provide good aesthetics and better fit compared to traditional methods (80).

A particularly interesting in-vivo study compared the comfort and satisfaction of twelve patients wearing two sets of removable full dentures, one 3D-printed and one conventionally fabricated with CoCr bases (81). Patients rotated through wearing both types of dentures. At the study's conclusion, only one patient preferred the conventional denture, and three had no preference. The 3DP denture bases, though identical in material and design, were found to be harder, denser, and exhibited better microstructural organization. They also showed improved clasp retention and denture stability due to higher yield strength and ultimate tensile strength.

3DP plays a crucial role in diagnostics, treatment planning, patient communication, skills training, and maxillofacial surgery (82, 83). Low-cost printers offer a practical alternative for in-house production, producing clinically acceptable provisional crowns and bridges (84), full arch models (85), and digital copies of plaster orthodontic models (86). These printers create realistic models with sufficient dimensional accuracy for various applications (82). They have also been successful in creating face masks for facial transplants, ensuring donor resemblance without jeopardizing the allograft (87). The integration of 3DP into digital dentistry has led to new material innovations. According to a comprehensive review by Galante et al., additive manufacturing of ceramics for dental applications remains under-researched (71). Another review found 1322 relevant papers on dental implant fabrication via additive manufacturing, but only 13 were deemed suitable for systematic review. This highlights the need for standardized methodologies to evaluate the efficacy of additive manufacturing in dental applications.

Workflow with CAD/CAM

The evolution of CAD/CAM systems has significantly altered workflows in dental restoration processes. While the functional components of data acquisition, design, and fabrication remain fundamentally the same, modern CAD/CAM systems offer a dramatically different approach to workflow, thanks to open architecture systems.

Open Architecture Systems: Traditionally, CAD/CAM systems operated as closed systems, integrating all functional components into a single system. Today, open architecture has created opportunities for users to select and link functional components from various manufacturers. This flexibility allows for a more tailored workflow, enabling the distribution of tasks according to the interests, capabilities, and skills of those involved in fabricating dental components. The digital workflow has demonstrated significant time savings from data acquisition to final product, with the greatest reductions observed in laboratory time (88, 89).

The Digital Virtual Patient as an Enabler

The integration of various digital technologies has expanded the possibilities within dentistry. The concept of the digital patient—created by integrating facial data, radiographic information, intraoral images, and other relevant data—has enabled advancements in computer-assisted surgery, CAD/CAM systems, one-appointment restorations, and tissue-engineered scaffolds.

Digital Patient: The digital patient integrates data from multiple sources to develop a comprehensive digital treatment plan. This platform allows for the design and simulation of procedures, including restoration design, surgical navigation, and craniofacial surgeries. The virtual patient reduces errors associated with conventional methods, decreases planning time, and enhances intuitiveness (90-93). Additionally, it enables clinicians and technicians to model and evaluate multiple configurations more efficiently than with traditional methods, which may cause damage to models and involve limited 3D data and manual manipulations. In orthognathic surgeries, planning with the virtual patient allows for high precision and optimization, resulting in more accurate surgical outcomes (95, 96). CAD/CAM systems can directly design and fabricate prostheses, surgical guides, models, and other structures based on this digital model.

Computer-Assisted Surgery/Dynamic Surgical Navigation

Computer-assisted surgery (CAS) represents a significant advancement enabled by digital technology. CAS uses navigation systems similar to GPS to track the real-time position of surgical devices (e.g., endodontic files, implants, scalpels) and project this information onto digital images of the anatomical area of interest. This guidance helps clinicians follow planned pathways and avoid interference with adjacent tissues. Optical tracking systems, which use light-emitting diodes mounted on surgical devices, are commonly used. For instance, the YOMI™ computerized navigation system, approved by the FDA in 2017, provides robotic guidance to enhance the skill and precision of implant surgery (97).

Dynamic surgical navigation has been shown to improve positioning accuracy for dental implants and reduce errors in various dental procedures (101-104). Mixed reality, which integrates virtual and augmented reality, further enhances visualization by combining real and virtual environments (105).

Mixed Reality: Mixed reality fuses real and virtual environments to enhance visualization during procedures. Technologies like Google Glasses and other VR equipment create immersive virtual spaces, while mixed reality integrates real-world elements into these virtual environments (105).

Robots Already in Dentistry

Robots have seen extensive use outside of dentistry, from autonomous package delivery to manufacturing and assembly. In medicine, robots have been used since 1992, with significant numbers of robotic surgeries performed annually (109). Although robotics in dentistry are less prevalent, there have been notable developments:

- **Early Robotics:** In 2001, a remote-controlled robot performed caries removal, crown and bridge preparation, and endodontic therapy (111).
- **Tooth Preparation:** Robots have been tested for accuracy in laminate veneer and crown preparations (112-114).
- **Wire-Bending Robots:** Introduced around the turn of the century, these robots have been used to create orthodontic wires. A recent mobile wire-bending machine can produce fixed orthodontic retainers in four minutes (115, 116).
- **YOMI™ Robot:** This robot, approved in 2017, guides implant surgery with high precision (97). In China, a robot dentist successfully inserted implants with 0.2–0.3 mm accuracy in a live patient (117).

A Different Approach to One-Visit Crowns and Bridges

One of the initial advantages of CAD/CAM systems was the ability to provide chair-side one-visit restorations. Traditional CAD/CAM systems required relatively long appointments for designing and fabricating restorations. However, a new approach introduced in 2017—FIRSTFIT™—shortens appointment times while still delivering high-quality crowns and bridges.

FIRSTFIT™ Approach: This approach involves sending digital impressions and bite registration, along with shade and characterization descriptions, to a laboratory before tooth preparation. The laboratory designs the preparation and creates 3D surgical guides for tooth preparation. Simultaneously, the definitive crown or bridge is designed and printed (typically from zirconia). The guides, a unique burr, and the final restoration are then sent to the dentist, who uses the guides to prepare the tooth and immediately seats the final restoration. A stone model of the patient's dentition is also provided for the dentist to verify the fit and technique. This method raises questions about managing unexpected intracoronal pathologies and the potential role of assistants in completing preparations. These advancements in CAD/CAM systems and digital workflows have significantly enhanced the precision, efficiency, and capabilities of dental restoration and surgical procedures.

Scaffolds and Tissue Engineering

Advancements in digital imaging and 3D printing technologies have profoundly impacted tissue engineering, particularly in craniofacial reconstruction. Integration of data from cone beam computed tomography (CBCT) and other imaging techniques with 3D printing has opened new possibilities for personalized scaffolding constructs.

Personalized Scaffolding:

- **Customized Constructs:** The use of patient-specific anatomical data allows for the creation of scaffolds that match the unique topography and internal geometry of the patient's anatomy. This includes tailoring the interconnected pore structure and adjusting mesoscopic and macroscopic porosity to meet specific needs (121, 122).
- **Stiffness Tuning:** Scaffold properties, such as stiffness, can be adjusted based on site-specific requirements to optimize performance (125).

Applications and Innovations:

- **Inter-Dental Scaffolds:** New developments have focused on scaffolds within root canals, with successful vasculogenesis achieved even with hand-held bioprinting systems. Micro-patterns of the human dentin-pulp complex have shown over 88% viability.
- **Bio-Inks:** Innovations in bio-inks enable the integration of live cells and temperature-sensitive pharmaceutical agents into scaffolds. Advances in extrusion-based bio-ink printing highlight improvements in biocompatibility, printability, and mechanical properties. Challenges remain in printing structures that effectively promote tissue and organ regeneration.

The field of scaffolds and tissue engineering is rapidly evolving, with digital dentistry playing a crucial role. The creation of scaffolds and engineered tissues represents a promising area for material science and regenerative medicine (126).

Conclusion

Advances in digital dentistry have dramatically transformed the landscape of dental practice, driving significant improvements in both clinical outcomes and patient experiences. The integration of digital technologies such as CAD/CAM systems, intraoral scanners, and additive manufacturing has revolutionized various aspects of dental care, from diagnosis and treatment planning to the fabrication of dental restorations. Intraoral scanners, for example, have replaced traditional plaster models with digital files that enhance the precision and efficiency of restorations. These scanners facilitate real-time imaging of the dental arch and surrounding tissues, providing clinicians with detailed visualizations that simplify patient communication and improve comfort during data acquisition. The accuracy of these digital impressions has been demonstrated to be comparable to conventional methods, with minor variations that remain within clinically acceptable limits. CAD/CAM systems have further expanded the capabilities of digital dentistry by enabling the design and production of a wide range of dental appliances and restorations. The shift from subtractive to additive manufacturing, particularly through 3D printing, has introduced new materials and design flexibility, allowing for the creation of complex geometries and personalized prostheses. Additive manufacturing has shown comparable, if not superior, accuracy in producing dental components, with applications ranging from temporary crowns to full dentures. The advent of open architecture systems has streamlined workflows by allowing for the integration of components from various manufacturers, optimizing the efficiency and customization of dental procedures. The concept of the digital patient, which integrates diverse data sources into a comprehensive digital model, has enhanced the precision of treatment planning and surgical navigation. Computer-assisted surgery and mixed reality technologies have further advanced the field by providing real-time guidance and immersive visualization during procedures. Overall, digital advancements in dentistry have led to substantial gains in accuracy, efficiency, and patient satisfaction. The ongoing evolution of these technologies promises continued improvements in dental care, with future innovations likely to push the boundaries of what is possible in restorative dentistry and personalized treatment.

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التقدم في طب الأسنان الرقمي: تأثير التقنيات المختلفة

الملخص:

الخلفية :لقد ثوَّرت التقنيات الرقمية العديد من المجالات، وطب الأسنان ليس استثناءً. لقد غيَّرت تكامل الأنظمة الرقمية المتقدمة في ممارسة طب الأسنان بشكل كبير سير العمل السريري ورعاية المرضى. تستعرض هذه المراجعة تأثير التقنيات الرقمية المختلفة على طب الأسنان، مع التركيز على التقدم والحالة الحالية للأنظمة الرقمية.

الهدف :الهدف من هذه المراجعة هو فحص التقدمات في طب الأسنان الرقمي، مع التركيز على التقنيات الرئيسية مثل أنظمة CAD/CAM، تقنيات التصوير، وبرامج إدارة الممارسات، وتأثيرها على الممارسة السريرية وعلوم المواد.

الطرق :تستعرض المراجعة المعلومات من مجموعة متنوعة من المصادر، بما في ذلك التطورات التاريخية والابتكارات التكنولوجية الحالية في طب الأسنان الرقمي. تشمل المجالات الرئيسية التي يتم التركيز عليها الماسحات الضوئية داخل الفم والمختبرات، أنظمةCAD/CAM ، التصنيع الإضافي، وتحسين سير العمل.

النتائج :لقد حسَّنت الأنظمة الرقمية بشكل كبير من دقة وكفاءة ترميمات وعلاجات الأسنان. توفر الماسحات الضوئية داخل الفم تصويرًا في الوقت الحقيقي ورؤى رقمية مفصلة، مما يعزز التواصل مع المرضى وراحتهم. توسعت أنظمة CAD/CAM لتشمل مجموعة واسعة من أجهزة الأسنان والترميمات. قدم التصنيع الإضافي، أو الطباعة ثلاثية الأبعاد، مواد جديدة وإمكانات تصميمية، مما ساهم في تطوير الأطراف الاصطناعية ونماذج الأسنان المعقدة. وقد أدت أنظمة البنية المفتوحة إلى تبسيط سير العمل، بينما حسَّنت التكنولوجيا الرقمية والعمليات الجراحية المدعومة بالحاسوب من الدقة في تخطيط وتنفيذ العلاج.

الخلاصة :أدى تكامل التقنيات الرقمية في طب الأسنان إلى تقدم كبير في الممارسة السريرية. توفر الأنظمة الرقمية الحديثة دقة وكفاءة ورضا مرضى محسَّن، مع استمرار الابتكارات في تشكيل مستقبل رعاية الأسنان. يعد التطوير المستمر لهذه التقنيات بمزيد من التحسينات في الإجراءات الترميمية وعلوم المواد والتخطيط الشخصي للعلاج.

الكلمات المفتاحية :طب الأسنان الرقمي، أنظمةCAD/CAM ، الماسحات الضوئية داخل الفم، التصنيع الإضافي، تحسين سير العمل، الجراحة المدعومة بالحاسوب، المريض الرقمي