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The digital workflow in dentistry: adoption and challenges

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Abstract

The incorporation of digital technologies has brought about a revolution in the profession of dentistry, resulting in greater diagnostic accuracy, enhanced patient outcomes and streamlined operations. Intraoral scanners, cone beam computed tomography (CBCT), computer-aided design/computer-aided manufacturing (CAD/CAM) systems, and 3D printing have profoundly influenced the field of prosthodontics, implantology and orthodontics. These developments provide enhanced precision in planning, manufacture and customization of dental prostheses and surgical guides. Nonetheless, the implementation of digital workflows entails problems such as elevated expenses, steep learning curves and the need for ongoing equipment maintenance. This study examines the advantages and obstacles of digital dentistry, emphasizes technological improvements, and considers future directions, including the potential for AI integration. A balanced approach, addressing the technological and clinical challenges, is crucial for maximizing the benefits of digital tools in modern dental practice.
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Keywords: *3D printing in dentistry, CAD/CAM, digital dentistry, digital workflow challenges, intraoral scanning, teledentistry*

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Introduction

In recent years, the dental industry has undergone a transformative shift with the widespread adoption of digital technologies. Technological advancements such as intraoral scanners, cone beam computed tomography (CBCT), and computer-aided design and manufacturing (CAD/CAM) systems have completely revolutionized dental practices (Reddy *et al.*, 2023; Wennerberg & Albrektsson, 2011) . These digital tools facilitate accurate diagnoses and treatment planning, improves patient communication, and streamlines the laboratory procedures for designing and fabricating prostheses. This article explores the profound impact of digital dentistry on enhancing patient experiences and treatment outcomes.

Digital data acquisition: intraoral and extraoral scanning

Digital workflow in dentistry begins with accurate digital data acquisition, with intraoral scanners playing a crucial role. Intraoral scanners provide numerous advantages by substituting the conventional analog impressions with accurate digital scans. They capture highly detailed 3-dimensional representations of oral tissues non-invasively, significantly enhancing patient comfort (Ahlholm *et al.*, 2018; Ahmed *et al.*, 2024; Andriessen *et al.*, 2014; Giachetti *et al.*, 2020; Nayar & Mahadevan, 2015; Seelbach *et al.*, 2013). These scans can be used to create digital models that can be easily edited, stored and shared (Kan *et al.*, 1999). Thus, improving information exchange between dental professionals, with patients, and with dental technicians, facilitating collaborative treatment planning and prosthetic design.

Practitioners without intraoral scanners who wish to access to digital workflow can alternatively adopt a “hybrid” approach by taking the conventional analog silicone impressions before scanning the impressions extraorally. Alternatively, they can first pour the silicone impressions into physical stone models followed by digital scanning with an extraoral or desktop scanner. This results in the acquisition of digital files that are similar to those obtained from intraoral scanners. This method highlights the versatility and adaptability of digital technologies in daily practice.

Integration of CBCT and advanced imaging in digital workflow

In addition to intraoral or extraoral scanning, CBCT is an essential tool for obtaining vital information that are helpful for treatment planning. By producing detailed 3-dimensional radiographic images of oral and maxillofacial structures, CBCT enables precise evaluation of bone volume, bone quality, and anatomical landmarks essential for implant planning (Kim *et al.*, 2005). The integration of intraoral scans with CBCT and other digital scans, such as facial scans, enhances case assessment and visualization, resulting in a more reliable treatment planning and optimized outcomes.

Precision in implantology: virtual planning and surgical guides

CBCT imaging has become indispensable in implantology, with virtually no implant procedure proceeding without prior CBCT assessment. Virtual implant planning software, integrated with CBCT, allows for precise planning of the implant fixture angulation and positioning within the residual bone (Andriessen *et al.*, 2014; Jemt and Lie, 1995; Reddy *et al.*, 2023). When the proposed plan is combined with surgical guide fabrication, fully guided implant placement workflow can be applied. This ensures an accurate 3-dimensional surgical placement of the implant fixtures thus minimizing surgical errors and complications. Moreover, with these digital tools, the position of implant can be planned accordingly to be prosthetically driven placement that will ease the final implant-supported prostheses fabrication. This approach exemplifies how digital dentistry enhances precision and predictability in complex dental procedures.

Digital Smile Design (DSD) and aesthetic dentistry

The integration of digital technologies in aesthetic dentistry has brought about a revolutionary change with the implementation of Digital Smile Design (DSD), which allows for the visualization and planning of smile makeovers. The use of facial scans, extraoral and intraoral photographs as well as intraoral scans in DSD allows for accurate individualized assessment of facial aesthetics, tooth proportions and gingival contours that suitable for patients. This method enables collaborative treatment planning among dental professionals and dental technicians, improving patient satisfaction by ensuring predictable results and personalized smile designs.

Teledentistry and remote consultations

Since the Covid-19 pandemic outbreak in 2019, the emergence of telecommunication technologies has facilitated the rise of teledentistry, enabling remote consultations, diagnosis, and treatment planning (Chu *et al.*, 2024). Dental professionals can utilize secure digital platforms to remotely evaluate patient conditions, offer virtual consultations, and engage in global collaboration with other specialists worldwide. Teledentistry enhances access to dental services, especially in remote areas, and ensures the ongoing provision of care to underserved populations.

A recent study on Malaysian dental professionals found that many were aware of the benefits of teledentistry, particularly its role in increasing accessibility and reducing patient chair time. However, barriers such as limited infrastructure, insufficient training, and concerns about diagnostic accuracy still hinder its widespread adoption (Chu *et al.*, 2024).

Digital orthodontics: aligners and virtual treatment planning

Since the introduction of clear aligner system and virtual orthodontic simulation and treatment planning software, the practice of orthodontics has been revolutionized by digital orthodontics. 3D models are generated by using intraoral scans and CBCT data to accurately simulate virtual tooth movements to facilitate precise treatment planning. CAD software enables the creation of personalized aligners, streamlining and ensuring the effectiveness of orthodontic treatments (Rajasekaran & Chaudhari, 2022). This digital workflow enhances patient comfort, compliance and treatment efficacy when compared to the conventional braces (Harikrishnan & Subramanian, 2023; Rajasekaran & Chaudhari, 2022; Vaid, 2018).

Digital endodontics: microscopic imaging and treatment planning

Digital endodontics combines the use of microscopic imaging, CBCT, and digital treatment planning to improve the accuracy and precision in root canal therapy. Advanced imaging systems with high resolution offer precise visibility of the intricate root canal structure, which greatly aids the accurate diagnosis and treatment planning. Utilizing digital software facilitates the process of measuring, sealing and evaluating the quality of the obturated canal post-endodontic, thus guaranteeing a higher success treatment rate (Mikrogeorgis & Delantoni, 2024). This contributes to better long-term outcomes, lowers retreatment rates, and enhances patient satisfaction through minimally invasive techniques.

Education and training in digital dentistry

Integrating digital technologies into dental education improves learning experiences and equips future dentists with modern clinical skills. Virtual reality simulations, augmented reality applications, and digital learning platforms offer interactive instruction in diagnostics, treatment planning, and procedures (Jahangiri *et al.*, 2020).

For example, the use of virtual simulation systems such as DentSim has been widely adopted in dental education globally to enhance psychomotor skills and clinical preparedness. These systems provide real-time feedback and objective assessment, helping students improve their operative techniques and decision-making abilities (Jahangiri *et al.*, 2020). Moreover, digital case-based learning modules and online CAD training allow dental students to master digital workflows, even remotely.

Continuing professional development through hands-on workshops and webinars further helps practicing dentists to stay updated with emerging technologies (Gross *et al.*, 2019).

Ethical and legal considerations

With the advancement of digital dentistry, there are emerging ethical and legal concerns related to patient privacy, data security, and informed consent. Compliance with regulatory requirements and rules guarantees the responsible utilization of digital technologies in dental practice (Rokhshad *et al.*, 2023). Providing education on ethical principles, patient rights, and data protection protections fosters ethical behavior and builds trust between dental practitioners and patients in the era of digital technology.

Digital fabrication: CAD/CAM and 3D printing technologies

Within the laboratory environments, Digital workflows optimize prosthesis production by simplifying design and manufacturing, ensuring precision, and reducing waste. Computer-aided design (CAD) software allows for virtual design of prostheses with high accuracy and customization (Sulaiman, 2020).

These digital designs can be fabricated through:

- **Subtractive manufacturing (milling)**: Uses milling machines to carve restorations from ceramic, composite, titanium, or zirconia blocks. Suitable for permanent restorations, implant abutments, and frameworks (Turkyilmaz & Wilkins, 2021).
- **Additive manufacturing (3D printing)**: Builds objects layer by layer using biocompatible resins, ceramics, or metals. Applicable in producing crowns, bridges, dentures, surgical guides, and clear aligners (Alharbi *et al.*, 2017; Rajasekaran & Chaudhari, 2022).

Both methods offer exceptional precision and faster turnaround times, enabling same-day restorations and improved patient satisfaction. They support a wide range of biocompatible materials and ensure restorations meet clinical and aesthetic demands (Galante *et al.*, 2019; Bae *et al.*, 2017).

Additive manufacturing (3D printing)

3D printing, often called additive manufacturing, has greatly transformed the production of dental prostheses and appliances. 3D printers use biocompatible materials like resin, ceramic, or metal powders to manufacture layers of material according to digital design generated by CAD software. This technology has multiple applications in the field of dentistry. It allows the production of personalized dental prostheses, such as crowns, bridges, and dentures (Alharbi *et al.*, 2017; Barazanchi *et al.*, 2017; Galante *et al.*, 2019; Revilla-León *et al.*, 2020; Tian *et al.*, 2021). By utilizing digital technology, designs may be customized to match the unique anatomy of each patient, guaranteeing an accurate fit and optimal comfort. Furthermore, 3D printing is also used in implant dentistry to provide accurate surgical guides that are based on virtual implant design. This enhances the precision of implant placement during surgery, minimizing procedural mistakes and improving the treatment outcomes. In addition, orthodontic appliances including as clear aligners and retainers are now being made more commonly using 3D printing technology (Rajasekaran & Chaudhari, 2022). Intraoral scans are utilized to create digital models, which are then employed to construct aligners. These aligners gradually reposition teeth, providing a more pleasant and visually pleasing alternative to conventional braces.

Subtractive manufacturing (milling)

Subtractive manufacturing in dentistry refers to the accurate subtraction of material from blocks or blanks with the use of computer-controlled milling machines (Turkyilmaz & Wilkins, 2021). This technique is predominantly utilized for permanent fixed restorations, implant abutments as well as removable prosthesis frameworks. Permanent restorations like crowns and bridges from ceramic or composite material can be milled easily from blocks. The technique guarantees exceptional precision and consistency of restorations, satisfying rigorous clinical standards for both fit and aesthetics. Besides, frameworks for fixed partial dentures (bridges) and implant-supported prostheses can be manufactured to uphold the functional and aesthetic elements of dental restorations. Moreover, implant abutments, which attaches the crown superstructure to the implant fixture, can be customized and designed accordingly and subsequently fabricated by milling titanium or zirconia blocks. This CAD/CAM technique guarantees the best possible fit and alignment with the implant platform, hence improving the stability and durability of the restoration (Aeran *et al.*, 2014; Braian *et al.*, 2018; Jeong *et al.*, 2018; Reddy *et al.*, 2023).

Advantages of CAM technologies in dentistry

Both additive and subtractive manufacturing techniques provide exceptional precision, ensuring that dental prostheses fit flawlessly and perform optimally (Aeran *et al.*, 2014; Alharbi *et al.*, 2017; Galante *et al.*, 2019; Jeong *et al.*, 2018). Digital workflows enable the customization of dental solutions to meet the specific demands of each patient, enhancing patient comfort and satisfaction through personalized care. These technologies also enhance productivity by reducing the production time required for dental prostheses. Thus enables the possibility of same-day restorations and reduces the need for patients to make multiple trips for appointments. Additionally, with the diverse and continuous advancement of dental materials, CAM systems have the capability to handle a broad spectrum of biocompatible materials, providing the flexibility to select materials that meet specific aesthetic and durability criteria (Bae *et al.*, 2017; Sulaiman, 2020; Turkyilmaz & Wilkins, 2021).

Future directions and challenges

In the future, progressive development in CAD/CAM technology will continue to stimulate innovation in dental practice. Potential advancements may prioritize the improvement of material choices, the streamlining of manufacturing techniques, and the incorporation of artificial intelligence for automated design and production. Nevertheless, the use of CAD/CAM technologies still requires careful consideration of factors such as the upfront expenses, the need for regular equipment upkeep, and the continuous training requirements for dental practitioners. To expand the adoption of digital manufacturing in dentistry, it will be necessary to address these issues by focusing on continuing education, technological assistance, and research collaboration.

Challenges and considerations

Although digital dentistry offers significant advantages, it also poses certain challenges and conflicts. Embracing digital technologies in dentistry necessitates a substantial commitment to acquiring knowledge and undergoing training. Dental professionals need to acquire expertise in utilizing new hardware and software, which can be intricate and time-consuming (Jahangiri *et al.*, 2020). Thorough training programs are necessary to ensure that professionals can efficiently utilize these technologies to attain the best possible outcomes. The learning curve might provide a challenge, especially for experienced professionals who are used to conventional approaches.

Furthermore, the cost implication is another significant factor to consider when implementing digital dentistry. The initial capital outlay for digital equipment, such as intraoral scanners, CBCT machines, and CAD/CAM systems, can be significant. Additionally, there are recurring expenses associated with software upgrades, upkeep, and consumable materials. Providing training to employees for the usage of new technology involves costs in terms of both time and money. These financial considerations can discourage certain dental clinics, especially smaller ones, from adopting digital dentistry

In terms of equipment maintenance and upkeep, regular checkup and calibration are necessary for digital dental equipment to ensure accuracy and longevity. This can be both expensive and time-consuming. Practice operations and patient care might be disrupted by downtime caused by

equipment failure or repair. Providing training for workers to handle simple problems and perform regular maintenance can help reduce these interruptions, but it also increases their level of responsibility.
Although digital dentistry provides improved accuracy, there may be disparities in reported results when compared to traditional procedures (Mehl *et al.*, 2021). Digital impressions and restorations may vary in accuracy due to factors such as equipment calibration, software algorithms, and operator competency. Establishing standardized methods and conducting ongoing research are essential to guarantee that digital workflows continually yield dependable and precise outcomes.

As the utilization of digital technology grows, it becomes crucial to ensure the privacy and security of patient data (Gross *et al.*, 2019). It is imperative to securely keep digital dental data, which encompass photographs and scans, in order to safeguard against unwanted access and breaches. Dental practices are required to adhere to regulatory standards, to protect patient information. Besides, complying with ethical principles and regulatory guidelines regarding the usage, storage, and exchange of digital data is crucial for upholding patient trust and professional integrity. Therefore, enforcing resilient cybersecurity protocols and providing comprehensive data protection training to employees are essential approaches for resolving these concerns.

Incorporating digital technologies into current dental workflows might pose difficult for some practitioners as the digital workflow is swiftly progressing, with ongoing breakthroughs in technology. Practices must modify and adapt their procedures to accommodate the introduction of new technology and software while keeping abreast with the most recent advancements. Implementing this integration may necessitate substantial modifications in practice administration, encompassing scheduling, record-keeping, and communication with patients and laboratories. Achieving a smooth integration without causing any disruptions to everyday operations requires meticulous planning and cooperation.

Although digital dentistry offers numerous advantages, including enhanced patient comfort and reduced treatment durations, some individuals may exhibit reluctance or doubt about new technological advancements (Radwan *et al.*, 2023). Efficient dissemination of information and instruction regarding the benefits of digital instruments can mitigate apprehensions and foster confidence. Validating the precision and effectiveness of digital operations can be further bolstered by showcasing case studies or testimonials from patients, hence increasing acceptance.

Lastly, utilizing digital technologies, specifically those related to manufacturing processes such as 3D printing and milling, might result in environmental consequences. The manufacturing and disposal of electronic devices, along with the utilization of consumables and resources, add to the ecological impact of this practice. Adopting sustainable methods, such as recycling materials and minimizing waste, can assist in alleviating these environmental problems.

Conclusion

The advent of digital dentistry has introduced a new era characterized by accuracy, effectiveness, and patient-focused healthcare. From the use of intraoral scanning to the process of virtual planning and CAD/CAM fabrication, these technologies have not only enhanced the results of dental treatments but also broadened the potential for personalized dental solutions tailored to individual patients. To fully leverage the promise of digital dentistry in improving dental practice worldwide, it is crucial to tackle problems by focusing on education, research, and technological improvement as developments progress and acceptance increases.

Despite the transformative benefits of digital dentistry, there are challenges and considerations that highlight the importance of a balanced approach to adoption. By addressing the steep learning curve, managing costs, ensuring data security, and staying current with technological advancements, dental professionals can fully leverage digital tools to enhance patient care and treatment outcomes. Continuous education, standardized protocols, and ethical practices will be key to maximizing the potential of digital dentistry in the ever-evolving landscape of dental care.

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