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Digital Technologies in Dental Implantology

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* Overview

Dental implantology is not an exception to the revolution in medicine and dentistry that has been facilitated by technological advancements. Dental implants are the major approach for replacing lost teeth because of their longevity, aesthetics, and function. Dental implants require precise surgical execution and rigorous treatment planning to be successful and accurate (Saini et al., 2024).

Careful planning and surgical placement of dental implants play an important role in ensuring positive outcomes and sustainable health for patients (Marlière et al., 2018). Consideration planning enables clinicians to perform a comprehensive assessment of the patient's oral and maxillofacial structure, identifying potential complications or obstacles during the procedure (Anand and Panwar, 2021). By assessing the quality and quantity of available bones, proximity to vital structures such as muscles and tendons, and the condition of adjacent teeth, clinicians can develop a treatment strategy that maximizes the chances that problems will be reduced (Jaju and Jaju, 2014).

In addition, careful planning facilitates the identification of optimal implant dimensions, contours, and orientation, while considering the functional needs and aesthetic desires of the individual (Kola et al., 2015). Furthermore, the process of osseointegration, where the implant fuses with the adjacent bone, is highly dependent on the precise surgical placement of dental implants (Parithimarkalaignan and Padmanabhan, 2013).

On the other hand, misalignment or inappropriate insertion of implants can cause mechanical and biological difficulties such as implant failure, bone loss, and soft tissue concerns. The proper site of the implant has a substantial impact on its overall endurance and dependability, which is required for optimal load distribution and optimum performance (Tallarico et al., 2020).

Conventional treatment planning in dental implantology often uses two-dimensional (2D) imaging methods such as panoramic and periapical radiography (Shah et al. 2014). Although these conventional approaches give useful information, they have limitations in adequately representing the 3D anatomy of the oral and maxillofacial areas (Beshtawi et al., 2021). This underrepresentation limits the ability to identify important anatomical features such as dental smooth muscle, alveolar bone morphology, and proximal dentition, which may increase the risk of complications during implant placement (Beshtawi et al., 2021). Consequently, three-dimensional (3D) imaging techniques, together with virtual patient models, have emerged as powerful tools in recent years to facilitate proactive planning. The accuracy and predictability of surgical and operative procedures have been enhanced in dental implants (Saini et al., 2024).

Furthermore, three-dimensional imaging techniques have enhanced routine preoperative radiographic examinations. It also increases accuracy in quantifying bone density and in assessing the proximity of adjacent anatomic structures (Tanveer et al., 2021). Thus, data from the 3D imaging system facilitates preoperative planning. This system enables precise implant placement guidance to optimize placement and angle to ensure that it is compatible with the prosthetic design. Further, it can protect the important adjacent anatomical structures (Mizrahi et al., 1998).

Digital design relies on computer-aided design (CAD) systems to refine the accuracy of implants. It optimizes the design of molds and models, and teaches objects attached to the implant surface, to facilitate the fabrication of custom implants using various implant software applications (Scolozzi et al., 2023). In addition, digital charts are an important tool for improving patient communication, which enables physicians to visually represent proposed treatment plans and engage in informed discussions about predicted outcomes results have been reported. Overall, the digitization of implant design reduces the potential errors inherent in traditional freehand techniques, increases accuracy, and aids drive the success and longevity of dental implant treatments (Saini et al., 2024).

Despite its advantages, several challenges may hinder the clinical application of virtual simulation and 3D imaging. These challenges include capital investment and ongoing maintenance costs associated with these devices, and the need for specialist personnel trained in the operation of these technologies. Notably, the use of this system will loosely integrate established clinical workflows. The development of user-friendly and economically viable imaging systems provides a potential solution to this obstacle (Saini et al., 2024).

Moreover, the comparative evaluation of digital dentistry versus conventional techniques is another considerable literature lacuna (Chochlidakis et al., 2016). Digital procedures are not explicitly compared to conventional approaches in a significant number of studies, which complicates the determination of the accuracy of digital dentistry (Tabesh et al., 2021).

*** Applications of 3D imaging devices**

*** Intraoral scanners**

three-dimensional (3D) optical scanning technologies, such as the intraoral scanner (IOS), have been developed for dental applications. These techniques may address patient discomfort, inherent inaccuracies, and the difficulties in acquiring realistic three-dimensional geometries of dental tissues using traditional two-dimensional (2D) imaging methods, (Gröndahl et al., 1996). In 1987, an early facial sensor capable of transferring X-ray images to a television monitor and an accompanying display processing unit appeared as an alternative to traditional radiography. Subsequent developments in sensor technology-enabled digital post-processing, facilitating the characterization of diverse diagnostic problems (Sanderink, 1993).

An intraoral scanner is used to directly acquire three-dimensional topographic color and texture data of the hard and soft tissues of the oral cavity, including teeth, gums, and mucous membranes (Mangano et al., 2017). Subsequently, computer-aided design and computer-aided manufacturing (CAD/CAM) software platforms can be used to process digitally captured images of patients' jaw structures. This may facilitate the fabrication of dental prostheses and the design and execution of the restoration (Mai et al., 2021).

In the case of dental implants, dental scanning systems can be used for digital planning and single and multiple dental implants (Yilmaz et al., 2023). The integration of digital scanning into clinical practice eliminates the need for traditional physical measurements. It also reduces the risk of microbial contamination and cross-infection and offers advantages such as reducing errors. Elimination of the tray selection process helps reduce the risk of infection, decreases staff workload, and improves patient comfort (Hou et al., 2022).

Numerous comparative studies have investigated the accuracy of digital versus conventional impressions, producing varied results. However, several investigations have indicated that digital impressions exhibit superior accuracy compared to traditional impressions, particularly in full-arch implant models (Hou et al., 2022).

*** Extraoral scanners**

As discussed earlier, the utilization of intraoral scanning systems can improve both the reliability and safety of guided implant surgery by facilitating the fabrication of computer-assisted surgical guides and enabling precise intraoperative implant identification (Schneider et al., 2009). While intraoral scanners capture data directly, extraoral scanners still require impression trays and materials to acquire information from the oral cavity. Therefore, extraoral scanners cannot fully eliminate adverse patient reactions, such as the gag reflex. Moreover, mitigating errors arising during model fabrication, such as dimensional changes post-polymerization and tray distortion presents a greater challenge with extraoral compared to intraoral scanning techniques (Ellakany et al., 2022).

However, unlike traditional design methods, face-to-face scanners prevent the need for two or multiple molds, reducing the risk of tray or cast deformation (Keul and Güth, 2020). Stefanelli et al. (2020) recommend the utilization of conventional postoperative radiological scanning for implant teeth positioning. This method gives the benefits of decreased radiation publicity by obviating the need for an extra cone-beam computed tomography (CBCT) test, improved time efficiency, and similar accuracy to established workflows.

Some proponents have suggested employing intraoral or extraoral scanners for implant tooth localization, and preliminary studies indicate satisfactory accuracy for postoperative verification; however, further research is necessary to definitively establish the clinical efficacy and efficiency of these devices (Zhou et al., 2020). Overall, despite their increasing prevalence in dentistry, the application of intraoral and extraoral scanners remains subject to limitations imposed by factors such as operator expertise, patient movement, restricted intraoral access, and potential distortion of the acquired images (Emir and Ayyıldız, 2019).

*** Cone-beam computed tomography**

A cone-beam computed tomography (CBCT) scanner is an imaging modality employing a collimated x-ray source to produce a cone- or pyramid-shaped x-ray beam. This beam undergoes a single, complete, or partial rotation around the patient, generating a series of discrete planar projection images acquired by a digital detector (Hou et al., 2022). The noninvasive nature of CBCT and the resultant enhanced patient comfort also contribute to its widespread utilization. By acquiring broad image data in a single scan, CBCT reduces the need for multiple imaging sessions, streamlines the diagnostic process, and improves the overall patient experience (Venkatesh and Elluru, 2017).

CBCT provides three-dimensional volumetric, surface, and sectional data acquisition capabilities. Advantages include rapid scan times, an expanded field of view, reduced spatial requirements, and lower associated costs. Significantly, CBCT offers the potential for reduced effective radiation dose and minimization of metal artifacts compared to conventional computed tomography (CT). This can be achieved through optimized patient positioning, like jaw tilting, and the use of supplementary protective measures such as thyroid collars (Hou et al., 2022).

Also, Oral implantology can benefit from the use of CBCT to enhance the detection and evaluation of anatomical structures in the planned implant location, as well as to achieve optimal implant placement. Additionally, CBCT imaging may be implemented to facilitate the early diagnosis and treatment of peri-implantitis (Hou et al., 2022). CBCT facilitates precise treatment planning by enabling accurate measurement and evaluation of available bone volume. Three-dimensional visualization of the implant site allows for the determination of optimal implant dimensions, orientation, and angulation, contributing to improved implant success and longevity (Angelopoulos and Aghaloo, 2011). Nevertheless, the applicability of CBCT is limited by several factors, such as the relatively high quantity of scattered radiation, the limited field size, and the limitations of the current reconstruction algorithms (Shaheen et al., 2017).

*** Facial scanners**

A facial scanner is a non-contact, non-invasive measurement device that acquires three-dimensional facial morphology data, including realistic skin textures and colors (Conejo et al., 2021). Historically, physical facial impressions utilizing elastomeric materials and gypsum casts were employed to create facial models. However, this method presented patient discomfort due to the obscuring of facial features during the impression-taking procedure (Hou et al., 2022).

The advantages of facial scanners involve their rapid, non-contact scanning capabilities, which are generally well-tolerated by patients. Furthermore, facial scanners have found widespread clinical application due to their high reliability and accuracy. However, resources, time, and space constraints may preclude their routine utilization in certain settings (Petrides et al., 2021). It is important to note that some facial scanners utilize radiation that can be harmful to the eyes to acquire 3D images. This presents a disadvantage due to the potential detrimental impact on patient health and well-being (Hou et al., 2022). The analysis of facial morphology is of critical importance in the preoperative diagnosis, postoperative evaluation, and symmetry analysis of craniomaxillofacial surgery (Hou et al., 2022).

Despite their benefits, facial scanners are subject to certain limitations. For instance, data gaps or artifacts, commonly referred to as "holes," can arise from challenges in capturing complex surfaces such as eyebrows, eyelashes, and hairlines. Although image processing software can often rectify minor imperfections, larger defects can hinder the image-stitching process and compromise data integrity (Mai and Lee, 2020).

*** Combined multiple 3D imaging devices**

Recent years have witnessed a shift towards virtually based workflows in clinical practice, accompanied by growing interest in the integration of 3D imaging modalities. These practices include intraoral scanners, extraoral scanners, cone-beam computed tomography (CBCT), and facial scanners. This combined approach enables clinicians to select the optimal device for acquiring the most accurate data from diverse tissue types, encompassing the facial skeleton, extraoral soft tissues, dentition, and surrounding intraoral soft tissues (Hou et al., 2022).

Superimposing digital impressions acquired via intraoral or extraoral scanners onto CBCT data allows for comprehensive analysis of implant positioning (Li et al., 2021) (Figure 1). However, the practicality and reliability of utilizing intraoral scanners for full-arch implant impressions remain to be fully elucidated (Hou et al., 2022). Photogrammetry has steadily gained traction in clinical practice. By superimposing the digital file representing the 3D implant position onto soft tissue data acquired through photogrammetric techniques, the intraoral scanner can generate an accurate impression of the edentulous implant site (Hou et al., 2022).

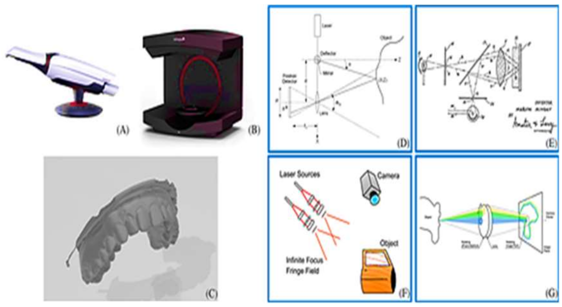

Figure 1. Combined multiple 3D imaging device techniques. (A) intraoral scanner (B) extraoral scanner (C) digital imprints from either intraoral or extraoral scanner. Four non-contact optical technology principles (D) Principles of triangulation, confocal microscopy, accordion fringe interferometry, and active wavefront sampling (Hou et al., 2022).

*** Computer-aided design and computer-aided manufacturing systems (CAD/CAM)**

Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies have facilitated implant placement for approximately 15 years. This 3D technology enables the fabrication of patient-specific surgical guides, providing preoperative planning data that can be utilized intraoperatively for precise implant placement (Derksen, 2023). Preoperative data for digital planning is typically acquired through non-contact three-dimensional imaging modalities such as computed tomography (CT), cone-beam computed tomography

(CBCT), and magnetic resonance imaging (MRI), as well as various laser scanning techniques (Tanveer et al., 2021).

Computer-aided manufacturing (CAM) builds upon computer-aided design (CAD) data, transforming virtual blueprints into tangible objects. This is accomplished through the fabrication of physical models, wax-ups, molds, surgical templates, or even direct prostheses using additive manufacturing techniques such as stereolithography (SLA) or fused deposition modeling (FDM) (Ishida et al., 2020). Sarment et al. (2003) reported that the utilization of CAD/CAM-fabricated surgical templates significantly enhances the precision and accuracy of dental implant placement compared to conventional surgical guides. Moreover, CAD/CAM technology has found recent applications in craniofacial implant surgery, demonstrating promising clinical results (Tanveer et al., 2021).

Additionally, CAD/CAM technology purportedly reduces the number of required patient consultations, shortens clinical and laboratory procedural timelines, and streamlines production stages without compromising clinical outcomes. Tanveer et al. (2021) employed CAD/CAM technologies for the fabrication of surgical templates, models, molds, substructures, customized implants, and guided implant procedures in the prosthetic rehabilitation of orbital defects.

However, the assessment of the impact of CAD/CAM on the fabrication of implants and prostheses reveals numerous literature gaps and controversies, necessitating additional scientific investigation. These voids are the result of a variety of factors, including the evolving and complex nature of digital dentistry technologies, the limited number of long-term clinical studies, and the diverse methodologies used in the extant research (Flügge et al., 2018).

*** Artificial intelligence in implant dentistry**

The concept of artificial intelligence (AI) was initially articulated at the Dartmouth Conference in 1956, defined as the cognitive capacity exhibited by human-created systems. AI strives to emulate, augment, and potentially surpass human intelligence in terms of cognitive functions and behavioral responses. This is achieved through the ability of AI systems to learn from and adapt to environmental stimuli (Xiaojun et al., 2021). Machine learning (ML), a subdomain of artificial intelligence, focuses on the development of algorithms capable of learning from input data and generating predictive outputs based on training. These algorithms are designed to extract patterns and identify relevant features from large datasets, while simultaneously filtering irrelevant information from the input sources (Choi et al., 2020).

On the other hand, deep learning (DL), predicated on artificial neural networks (ANNs), has garnered significant attention due to its advanced capacity to learn from input data. Unlike traditional machine learning (ML) models, DL utilizes layered data abstractions to construct complex computational models. This approach often results in shorter testing times compared to existing ML algorithms (Sarker, 2021).

Clinical medicine was extensively implemented with AI, which can encompass the fields of clinical medicine and dentistry due to its high efficacy and capacity to address intricate conditions (Mörch et al., 2021). Artificial intelligence has found widespread application in dentistry, contributing to advancements in both diagnosis and treatment. Various AI classifications have emerged, facilitating applications such as the diagnosis of cysts and tumors, and the detection and classification of dental caries and periapical lesions. Other applications involve the diagnosis of gingivitis and periodontitis, orthodontic treatment planning, pediatric dentistry, the segmentation of natural teeth and maxillofacial structures, guidance for dental professionals and researchers, and public oral health education (Mörch et al., 2021; Tay et al., 2023).

Moreover, the integration of artificial intelligence (AI) into implant planning heralds a new paradigm of enhanced efficiency and precision. AI algorithms enable clinicians to analyze extensive patient datasets, including radiographic images, three-dimensional scans, and clinical records, facilitating evidence-based decision-making regarding implant placement (Bonny et al., 2023). AI also offers predictive modeling and simulation capabilities, allowing clinicians to preview the projected outcomes of various treatment strategies before performing any intervention. This facilitates personalized, patient-specific treatment and enhances the overall planning process (Dhopte and Bagde, 2023).

Despite the potential advantages, the widespread adoption of AI in implant planning raises important ethical, legal, and practical considerations. Key challenges including data privacy, algorithmic transparency, and liability, must be addressed to ensure the responsible and ethical implementation of AI technologies in dentistry (Pethani, 2021). However, the efficacy of AI models in predicting implant prognosis remains to be fully established. A comprehensive evaluation of the performance and limitations of AI models for predicting dental implant outcomes is recommended to support clinicians in their decision-making processes (Wu et al., 2024).

In conclusion, the integration of digital technology has considerably changed the design of dental implants, from initial diagnostic imaging to final prosthetic reconstruction. Advances in 3D imaging (external scanners, CBCT), CAD/CAM systems, and the application of AI manage growing applications for unprecedented accuracy, predictability, and efficiency. This technology addresses the limitations of traditional methods, reducing risks, improving patient comfort, and contributing to enhanced treatment outcomes and long-term implant success. Further research is needed to refine existing technologies, address limitations such as image distortion and data gaps, and explore the full potential of AI in transplant management and prognostic prediction. Also, ethical considerations of data privacy, algorithmic transparency, and accountability are needed to ensure that these are used profitably in responsible tools are powerful. As digital technologies continue to evolve, ongoing research and clinical inclusion workflows will become necessary to maximize the positive impact on implants, and most importantly, the patients who benefit from these improvements.

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