ADVANCES IN DIGITAL TECHNOLOGIES APPLIED TO IMPLANT-PROSTHETIC REHABILITATION

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Abstract

Aim of the narrative review was to analyze digital systems in implant-prosthetic therapy, with a focus on diagnosis, pre-implant surgical planning, implant positioning, prosthetic workflow, biomechanical evaluation, and long-term monitoring. This narrative review was conducted based on a bibliographic search performed in PubMed/MEDLINE and Web of Science. The reviewed studies showed that digital systems support the main stages of implant-prosthetic rehabilitation, from pre-implant diagnosis and surgical planning to prosthetic design and postoperative monitoring. CBCT, intraoral scanning, CAD/CAM workflows, guided surgery, contributed to improved three-dimensional assessment, implant positioning accuracy, biomechanical evaluation, and clinical predictability. Digital systems support the implant position planning, occlusal analysis, prosthetic design optimization, complication risk assessment, and postoperative monitoring. The digital systems are useful tools in contemporary implant-prosthetic therapy, contributing to precision, patient safety, and workflow improvement. However, their clinical application relies on image quality, scientific validation, and the decision-making responsibility of the dental specialist.

Key words: edentulism, prosthetics, implantology, planning, digital techniques

INTRODUCTION

Digital dentistry marks a significant shift in modern stomatology toward greater accuracy and personalization, reshaping the way contemporary dental practice responds to growing clinical demands — among them, the expectation for fast, high-quality treatments and solutions adapted to each patient's specific situation [1-5]. Over the past two decades, digital technologies have been progressively integrated across the main fields of dentistry, expanding the range of available therapeutic options, improving treatment predictability, and bringing tangible benefits to both clinicians and patients [6–10].

At the level of clinical workflow, the contributions are concrete. Optical impressions have replaced conventional materials, CAD/CAM systems have shortened fabrication timelines while maintaining accuracy, and advanced imaging has made treatment planning more transparent and communicable. The breadth of rehabilitative options has expanded accordingly — from complex fixed prosthetics to fully guided implant-supported solutions — with outcomes that are both functionally reliable and aesthetically predictable [11, 12].

Digital technologies have also supported a broader movement toward conservative and minimally invasive

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clinical approaches, reducing operating time and procedural invasiveness in a range of interventions [11, 12]. Three-dimensional imaging modalities — from CBCT to intraoral scanning — provide the spatial data required for precise surgical and prosthetic planning, substantially reducing clinical uncertainty at each stage of treatment [11]. Contemporary digital systems further allow assessment of occlusal force distribution, mandibular movement dynamics, and the biomechanical behavior of prosthetic structures under functional load. When imaging volumes are combined with intraoral scan data, the resulting three-dimensional analysis of bone support and soft tissue architecture forms the foundation for individualized, evidence-informed rehabilitation planning [12].

Aim of research was to review the advancess in digital technologies and their applications in implant-prosthetic therapy, with focus on their contribution to diagnosis, pre- surgical stage, virtual implant positioning, digital workflow, long-term clinical monitoring.

MATERIALS AND METHODS

The bibliographic search was performed in international scientific databases PubMed/MEDLINE and Web of Science. The search strategy included combinations of keywords related to the main topic: “digital dentistry” AND “implant-prosthetic therapy”, “CBCT” AND “implant planning”, “cone-beam computed tomography” AND “bone augmentation”, “intraoral scanning” AND “CAD/CAM”, “guided implant surgery”, and “postimplant monitoring” AND “dental implants”. The selection protocol included scientific articles, reviews, clinical studies addressing digital workflows, CBCT-based planning, intraoral scanning, CAD/CAM technologies, static and dynamic guided implant surgery, prosthetic design, occlusal evaluation, and postimplant monitoring. The selected data were analyzed and organized according to the main clinical stages of implant-prosthetic rehabilitation. No date restriction was applied, in order to capture both foundational contributions and current clinical evidence; in practice, however, priority was given to publications from the past fifteen years, reflecting the period of most substantial development in digital implant-prosthetic workflows. Only articles published in English were considered.

The selection criteria encompassed scientific articles, systematic reviews, meta-analyses, randomized controlled trials, and clinical studies addressing digital workflows, CBCT-based planning, intraoral scanning, CAD/CAM technologies, static and dynamic guided implant surgery, prosthetic design, occlusal evaluation, and postimplant monitoring. Case reports were considered only where they provided data on specific digital applications not otherwise covered by higher-level evidence. Studies focused exclusively on implant biomaterials or surface topography without direct relevance to digital clinical workflows were excluded, as were publications not available in English.

The retrieved data were analyzed and organized according to the principal clinical stages of implant-prosthetic rehabilitation — from pre-surgical planning and guided surgery through prosthetic design, fabrication, occlusal analysis, and postoperative follow-up — in order to provide a structured and clinically

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applicable overview of current digital technologies in this field.

LITERATURE REVIEW

The clinical advantages of digital techniques in the pre-prosthetic surgical stage are well established and span the entire treatment sequence: three-dimensional accuracy in site assessment, reduced incidence of neurovascular injury, more reliable surgical planning and execution, earlier detection of oral pathology, and more structured postoperative monitoring [13].

Treatment planning has been refined by the introduction of digital technologies capable of suggesting optimal intervention timing, stratifying risk for specific complications such as paresthesia or jaw fracture, and supporting the selection of the surgical approach most suited to each patient's anatomy [14, 15].

Among the available imaging modalities, CBCT has become the reference standard for pre-implant evaluation. Before placement, it provides a three-dimensional picture of the alveolar defect — residual bone height, width, morphology, and density — that two-dimensional imaging simply cannot replicate [16]. This spatial information is directly relevant to the choice of bone augmentation procedure, as it defines not only the volume of bone required but also its relationship to structures that carry significant surgical risk: the maxillary sinus, the nasal floor, and the mandibular canal [17]. In practical terms, CBCT-based planning translates into better access, fewer intraoperative surprises, and a more accurately prepared implant site when the prosthetic phase begins [18-20].

Mandibular movement monitoring systems („Jaw Tracking") such as Zebris JMA (Zebris Medical GmbH, Germany) and JT-3D (BioResearch Associates, USA), enable dynamic three-dimensional analysis of mandibular movements during mastication and phonation, capturing precise trajectories of opening, closing, lateral, and protrusive movements. They allow visualization of complex functional movement data (mastication, speech), measurement of gnathological parameters, correlation with diagnoses obtained through other digital techniques (e.g., combining electromyography with JT-3D), and patient communication before and after treatment. Jaw tracking systems can detect functional anomalies and movement limitations, with direct relevance to the diagnosis of articular and mixed forms of stomatognathic dysfunction syndrome. The combination of CBCT imaging with 4D kinematic recordings (Modjaw) enables visualization of actual condylar bone movement within the fossa during mastication and phonation. Dynamic visualization allows detection of the precise moment at which the condyle displaces over or becomes blocked by the disc, supporting the design of occlusal devices that guide condylar movement along a non-traumatic path [21]. The Modjaw/Zebris system replaces mechanical articulators based on average angle settings by capturing a functional record of the mandibular trajectory, analyzing and simulating mandibular kinematics, and enabling the design of occlusal surfaces that respect individual dental movement envelopes — thereby eliminating the need for occlusal adjustments at the end of treatment. Data obtained through these systems are exported directly to virtual articulators, allowing CAD/CAM

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fabrication of customized occlusal splints. Optical recording of mandibular movements demonstrates superior accuracy compared to traditional techniques, with reduced discrepancies and interferences in occlusal splint fabrication, improving treatment efficiency and clinical outcomes [22]. ARCUSdigma II/III (KaVo Dental, Germany), a digital facebow system, records the position of the maxilla in relation to the cranial base, with the purpose of transferring data to CAD/CAM software. Kinematic face bows enable three-dimensional diagnosis and accurate positioning of the maxillary model in the articulator, offering the possibility of individualized dynamic evaluation of occlusion in relation to the hinge axis, through calculation of distances between the occlusal plane and the axis of rotation, and subsequent transfer of clinical data to the articulator. The ARCUSdigma system offers significant advantages for specialists in prosthodontics and implantology, allowing rapid, precise, and reliable recording of maxillary position. The clinician can apply the facebow in under three minutes, without the need for a dental assistant. ARCUSdigma 3 software calculates dynamic setting parameters for positioning the model in the PROTARevo articulator. The system eliminates the positioning difficulties associated with conventional mechanical facebows. The ARCUSdigma software transfers dynamic gnathological parameters to the individualized articulator models. This efficient workflow contributes to minimizing the occlusal adjustments required after treatment delivery, particularly in cases of increased or collapsed vertical dimension of occlusion. The technique allows precise analysis of condylar movements and is compatible with the majority of digital design systems used for the fabrication of occlusal splints, fixed prostheses, and functional appliances [23]. Cadiax Compact II (Cadiax Diagnostic — Gamma Dental, Austria) is an electromechanical device for recording condylar movements that captures and analyzes mandibular trajectories in all three spatial planes, providing precise information about temporomandibular joint mobility. The system is particularly useful in the assessment of condylar asymmetries, joint blockages, and movement limitations, contributing to the planning of occlusal and functional orthopedic therapies. In cases where temporomandibular disorders of muscular origin manifest as pain without evident limitation of mandibular movements, with incipient dysfunctions that are difficult to detect clinically, mandibular kinematics can be investigated through the Cadiax Diagnostic electronic axiography system. Cadiax has been shown to produce reproducible results in the assessment of mandibular movements in patients diagnosed with TMD [24]. A research group evaluated the presence of qualitative anomalies in mandibular movements in a group of patients with temporomandibular disorders that had not been detected through conventional clinical examination. They concluded that, although all patients presented normal mandibular movement amplitude, qualitative anomalies of mandibular kinematics were detected in patients with myogenic temporomandibular disorders using the Cadiax device — including movement deviations, condylar asymmetries, and discrepancies between centric position and maximum intercuspation [25].

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Virtual implant placement systems add another layer of pre-surgical verification, though it bears noting that full automation of this process remains unreported and scientifically unvalidated at present [26]. On the postoperative side, digital monitoring applications allow sequential assessment of wound healing, early recognition of infection-related changes, and structured follow-up of osseointegration — moving surveillance from a largely subjective clinical impression toward a more objective and traceable process [27].

A range of dedicated software platforms — Implant 3D (Media Lab), NobleGuide (Nobel Biocare), Virtual Implant Placement (BioHorizons), and ImplantMaster (iDent), among others — have brought these capabilities into routine clinical use, supporting both accurate implant positioning and the downstream design of prosthetic restorations. Through CBCT-based analysis, these systems allow precise measurement of alveolar bone dimensions, quantification of bone density, and reliable identification of anatomical structures whose preservation is non-negotiable during surgery [28]. Taken together, CBCT-integrated digital workflows are now a cornerstone of accurate diagnosis, safer surgical execution, and predictable implant-prosthetic rehabilitation [29].

Computer-aided implant surgery has developed along two distinct lines. Static-guided surgery uses a physical surgical stent to direct the osteotomy according to the preoperatively planned virtual implant position, while dynamic-guided surgery replaces the physical guide with an optical tracking system that displays implant osteotomy progress in real time on a monitor. Each approach has its own clinical strengths and its own set of challenges [30].

Three-dimensional navigation offer two particularly valuable functions: real-time visualization and control of the surgical guide, and more precise implant placement through interface-guided procedures [31]. These augmented reality-based devices support the surgeon by rendering virtual intraoperative images of the surgical field — images that can be interactively adjusted and interpreted using available digital data [32]. Beyond improving spatial orientation during surgery, augmented reality guidance has been shown to reduce the risk of implant failure, shorten operative time, and lower treatment costs. Compared to conventional two-dimensional navigation, augmented reality-guided implant placement has demonstrated significantly greater positional accuracy and reduced working time [33]. Applications extend beyond implantology: in orthognathic surgery, head-mounted displays have been used to provide partial visual immersion during complex procedures [34]. Their practical advantages include continuous feedback on bur depth and angulation, automatic recording of patient data and applied procedures, integration of planning and navigation within a single software environment, access to extensive implant libraries, and the ability to measure and analyze bone density directly [35].

The growing adoption of intraoral scanners has, in parallel, made digital impressions a routine part of clinical workflows. Their appeal rests on a combination of factors — accuracy, reduced chairside time, streamlined workflows, and, not insignificantly, better patient acceptance compared to conventional impression

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materials. Direct and indirect restorations produced from digital impression data have demonstrated clinically acceptable marginal gaps [36], and for CAD/CAM-fabricated zirconia crowns and three-unit fixed dental prostheses, digital impressions have been shown to deliver significantly greater accuracy of marginal and internal fit with reduced working time [37].

CAD/CAM technologies have fundamentally changed the design and fabrication of implant-supported prostheses. Modern CAD software enables the creation of highly customized restorations that integrate functional and aesthetic considerations, while advanced manufacturing methods, such as milling and 3D printing, provide restorations with exceptional fit and consistency. The range of materials available for CAD/CAM prosthetics has expanded to include high-strength ceramics like zirconia, as well as hybrid materials and biocompatible polymers, allowing for tailored solutions based on specific clinical requirements. Innovations such as the "one-abutment, one-time" protocol support soft tissue preservation and improved aesthetic outcomes, although long-term studies are needed to confirm their superiority. Fully digital workflows, integrating digital impressions and CAD/CAM fabrication, have been shown to produce restorations with better marginal fit and higher patient satisfaction compared to conventional methods [38-43].

Systems such as T-Scan allow real-time recording of occlusal force distribution — information that is directly relevant to preventing functional imbalances in rehabilitated patients. Advanced imaging modalities, including optical coherence tomography and high-resolution three-dimensional scanning, enable quantification of bone loss and monitoring of surface changes over time, supporting the management of complex and long-term cases [44].

Digital Smile Design adds an aesthetic dimension to this planning toolkit, serving as a motivational mock-up reference that guides the design of prosthetic restorations in accordance with established aesthetic principles and the individual patient's expectations [45].

CONCLUSIONS

Digital techniques have advantages of improving diagnostic accuracy, individualizing treatment planning, and increasing clinical predictability in the implant-prosthetic rehabilitation. The combined use of CBCT, intraoral scanning, CAD/CAM technologies, and surgical guidance systems allows for evaluation of muco-osseous supprt and prosthetic field. These data allows pre-implant surgical preparation and virtual implant positioning more effective comparing to conventional methods. The reliability of these technologies depends directly on the quality of the data from which they work, the degree to which individual applications have been clinically validated, and — perhaps most importantly — the capacity of the treating clinician to critically interpret digital results and exercise sound judgment at every decision point.

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