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CONTEMPORARY DIGITAL IMPLANT DENTISTRY: FROM VIRTUAL PLANNING TO THE CLINICAL-LABORATORY WORKFLOW

IMPLANTODONTIA DIGITAL CONTEMPORÂNEA: DO PLANEJAMENTO VIRTUAL AO FLUXO CLÍNICO-LABORATORIAL

IMPLANTOLOGÍA DIGITAL CONTEMPORÁNEA: DE LA PLANIFICACIÓN VIRTUAL AL FLUJO CLÍNICO-LABORATORIAL

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ABSTRACT

The objective of this article is to describe the fundamentals of digital implantology and the clinical-laboratory workflow involved in the integration of cone-beam computed tomography (CBCT), intraoral scanning, virtual planning, and the fabrication of surgical guides using CAD-CAM technologies. Digital implantology is based on Computer-Assisted Implant Surgery (CAIS), defined as a comprehensive workflow that encompasses essential diagnostic and preoperative planning steps to achieve predictable and safe results. This paradigm has consolidated restoratively driven planning, in which the three-dimensional positioning of the implant is subordinated to the aesthetic and functional requirements of the future prosthesis. The process begins with the acquisition of volumetric data via CBCT, allowing for a detailed analysis of bone volume and critical anatomical structures. Simultaneously, intraoral scanning captures the surface of soft tissues and teeth, replacing conventional physical impressions. The integration of these examinations enables the construction of the virtual patient, a stage currently optimized by artificial intelligence algorithms to ensure precise three-dimensional registration between different datasets. In the Computer-Aided Design (CAD) stage, a customized surgical guide is designed based on the virtual planning. The device is materialized via Computer-Aided Manufacturing (CAM), utilizing 3D printing or milling technologies with biocompatible resins. The execution of static guided surgery (s-CAIS) provides high accuracy in transferring digital coordinates to the operative field; thus, its primary development aims to ensure three-dimensional accuracy in transferring the virtual plan to the surgical field, regardless of the flap technique selected. It is concluded that the technological integration between CBCT, scanning, and CAD-CAM systems enhances biorestorative predictability and clinical safety in implant-supported rehabilitations.

KEYWORDS: Digital Implantology. Guided Surgery. CAD-CAM. Dynamic Navigation. Immediate Loading. Reverse Planning.

RESUMO

O objetivo deste artigo é descrever os fundamentos da implantodontia digital e o fluxo clínico-laboratorial envolvido na integração entre tomografia computadorizada de feixe cônico (CBCT), escaneamento intraoral, planejamento virtual e confecção de guias cirúrgicos por tecnologias CAD-CAM. A implantodontia digital fundamenta-se na Cirurgia Assistida por Computador (CAIS), definida como um fluxo de trabalho abrangente que engloba etapas essenciais de diagnóstico e planejamento pré-operatório para atingir resultados previsíveis e seguros. Este paradigma consolidou o planejamento protético guiado, no qual o posicionamento tridimensional do implante é subordinado aos requisitos

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estéticos e funcionais da futura prótese. O processo inicia-se com a aquisição de dados volumétricos por CBCT, permitindo a análise detalhada do volume ósseo e de estruturas anatômicas críticas. Simultaneamente, o escaneamento intraoral captura a superfície dos tecidos moles e dentes, que substituem as moldagens físicas convencionais. A integração desses exames permite a construção do paciente virtual, etapa otimizada por algoritmos de inteligência artificial para garantir um registro tridimensional preciso. No estágio de Desenho Assistido por Computador (CAD), projeta-se o guia cirúrgico personalizado baseado no planejamento virtual. O dispositivo é materializado via Manufatura Assistida por Computador (CAM), utilizando tecnologias de impressão 3D ou fresagem. A execução da cirurgia guiada estática (s-CAIS) proporciona alta acurácia na transferência das coordenadas digitais para o campo operatório, assim, seu desenvolvimento primário visa garantir a precisão tridimensional na transferência do planejamento virtual para o campo operatório, independentemente da técnica de retalho escolhida. Conclui-se que a integração tecnológica entre CBCT, escaneamento e sistemas CAD-CAM eleva a previsibilidade biorestauradora e a segurança clínica das reabilitações sobre implantes.
***PALAVRAS-CHAVE**: Implantodontia Digital. Cirurgia Guiada. CAD-CAM. Navegação Dinâmica. Carga Imediata. Planejamento Reverso.*

RESUMEN
El objetivo de este artículo es describir los fundamentos de la implantología digital y el flujo de trabajo clínico-laboratorial involucrado en la integración de la tomografía computarizada de haz cónico (CBCT), el escaneo intraoral, la planificación virtual y la fabricación de guías quirúrgicas mediante tecnologías CAD-CAM. La implantología digital se fundamenta en la Cirugía de Implantes Asistida por Computadora (CAIS), definida como un flujo de trabajo integral que abarca etapas esenciales de diagnóstico y planificación preoperatoria para alcanzar resultados predecibles y seguros. Este paradigma ha consolidado la planificación guiada por la restauración, en la cual el posicionamiento tridimensional del implante se subordina a los requisitos estéticos y funcionales de la futura prótesis. El proceso se inicia con la adquisición de datos volumétricos mediante CBCT, lo que permite un análisis detallado del volumen óseo y de las estructuras anatómicas críticas. Simultáneamente, el escaneo intraoral captura la superficie de los tejidos blandos y de los dientes, sustituyendo las impresiones físicas convencionales. La integración de estos exámenes permite la construcción del paciente virtual, una etapa actualmente optimizada por algoritmos de inteligencia artificial para garantizar un registro tridimensional preciso entre diferentes conjuntos de datos. En la etapa de Diseño Asistido por Computadora (CAD), se diseña una guía quirúrgica personalizada basada en la planificación virtual. El dispositivo se materializa mediante Manufactura Asistida por Computadora (CAM), utilizando tecnologías de impresión 3D o fresado con resinas biocompatibles. La ejecución de la cirugía guiada estática (s-CAIS) proporciona una alta precisión en la transferencia de las coordenadas digitales al campo operatorio, así, su desarrollo principal busca garantizar la precisión tridimensional en la transferencia de la planificación virtual al campo quirúrgico, independientemente de la técnica de colgajo seleccionada. Se concluye que la integración tecnológica entre CBCT, escaneo y sistemas CAD-CAM aumenta la predictibilidad biorrestauradora y la seguridad clínica en las rehabilitaciones implantosoportadas.
***PALABRAS-CLAVE**: Implantología Digital. Cirugía Guiada. CAD-CAM. Navegación Dinámica. Carga Inmediata. Planificación Reversa.*

1- INTRODUCTION

The evolution of contemporary implant dentistry is marked by the transition from an initial, strictly surgical focus to an integrated approach centered on long-term biological, functional, and esthetic success (1,2). This new paradigm seeks synergy among the prosthesis, the characteristics of the peri-implant tissues, and patient satisfaction (3,4). Currently, the use of digital technologies has been widely

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adopted to allow a comprehensive visualization of the residual anatomy in relation to the future rehabilitation prior to any intervention (5,6).

The concept of reverse planning (top-down) has consolidated as a preferred strategy, in which the planned position of the implant is determined by the final prosthetic restoration (7,8). This method allows factors such as aesthetics, occlusal function, and ease of hygienic maintenance to be prioritized over bone volume alone (7,9). Planning that disregards the virtual design of the prosthesis can lead to inadequate positioning, thereby increasing the risk of mechanical complications and even peri-implant diseases (8,9).

Three-dimensional diagnosis is based on the use of cone-beam computed tomography (CBCT), which provides detailed information about bone dimensions and the pathway of critical anatomical structures (10,11). Unlike 2D imaging, CBCT allows for multiplanar and curved reconstructions that assist in identifying anatomical variations, making it essential for selecting the appropriate implant diameter and length (2,10). This diagnostic precision ultimately promotes greater predictability and safety throughout the procedures (1,12).

The integration of CBCT with intraoral scanning (IOS) optimizes the digital registration of dental arches, overcoming the limitations inherent in conventional physical impressions (13,14). IOS accurately captures soft tissue topography and the position of remaining teeth, enhancing patient comfort (13,15). Additionally, these datasets yield virtual models that serve as the foundation for CAD software design and the fabrication of precision devices (10,16).

The merging of DICOM files (CBCT) and surface STL/PLY files (IOS) represents the cornerstone for constructing the 'virtual patient' (2,6). Dedicated software utilizes algorithms to superimpose these datasets into a single three-dimensional coordinate system (7,10), enabling clinicians to manipulate 3D models to optimize emergence profiles and occlusal load distribution, ensuring the virtual plan aligns with clinical reality (2,17).

Despite advances in predictability, implementing the digital workflow presents challenges, such as cumulative errors arising during data registration, software processing, or guide fabrication (9,18). Transitioning to these technologies requires a specific learning curve and the mastery of biological and technical principles to ensure that the final outcome faithfully reproduces the virtual plan (19,20). Therefore, there is a clear need to structurally organize the clinical-laboratory workflow and understand the sources of inaccuracy to maximize the efficacy of digital implant dentistry (4).

The aim of this article is to describe the fundamentals of digital implant dentistry and the clinical-laboratory workflow involved in the integration of CBCT, intraoral scanning, virtual planning, and CAD-CAM surgical guide fabrication.

2- METODOLOGY

This narrative review was conducted through a structured literature search focusing on the digital workflow in implant dentistry, spanning from three-dimensional diagnosis to final prosthetic rehabilitation. The selection of sources prioritized evidence published between 2010 and 2026, aiming to capture the most recent technological advancements in computer-assisted implant surgery (CAIS)

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and additive manufacturing. The databases searched included PubMed/MEDLINE and Scopus, utilizing English and Portuguese search terms such as 'computer-assisted implant surgery', 'guided surgery', 'digital workflow', and '3D printing'.

Inclusion criteria comprised prospective clinical studies, randomized clinical trials, systematic reviews with meta-analysis, and case reports describing the integration of DICOM and STL datasets for constructing the 'virtual patient'. Articles specifically addressing static computer-assisted implant surgery (s-CAIS) and dynamic navigation (d-CAIS) modalities were selected, as well as immediate loading protocols and CAD-CAM customization of prosthetic components. Additionally, investigations into novel biomaterials and emerging technologies, such as mixed reality and artificial intelligence, were included.

The analysis and synthesis of information were performed in a thematic manner, organizing the content into sequential clinical steps to facilitate comprehension of the complete digital workflow. The articles were evaluated regarding their technical relevance and contribution to the predictability of clinical outcomes, with a particular focus on implant placement accuracy and soft tissue stability.

3- DATA COLLECTION AND THREE-DIMENSIONAL DIAGNOSIS

Clinical and Systemic Evaluation

Success in contemporary digital implant dentistry begins with a comprehensive diagnostic evaluation, based on a detailed collection of the patient's medical, dental, and psychosocial history (3). This step is indispensable for establishing an individualized risk profile and selecting candidates who do not present severe local or systemic contraindications to surgical intervention (12,21). Initial screening identifies chief complaints, such as masticatory insufficiency or aesthetic dissatisfaction, allowing the digital planning to be tailored to meet the individual's realistic expectations and values (3,5).

The analysis of systemic conditions is critical, particularly in patients taking medications with a direct impact on bone metabolism or coagulation. Individuals with a prolonged history of antiresorptive therapy require rigorous clinical management and an in-depth risk-benefit analysis to mitigate the risk of osteonecrosis of the jaw (22,23).

Surgical risk stratification is routinely performed using the American Society of Anesthesiologists (ASA) classification, with the digital workflow being frequently applied to ASA I or II patients (6,18). Stable systemic conditions, such as mild hypertension and controlled diabetes, safely permit the execution of advanced immediate loading protocols (24). Preoperative planning must confirm that the patient's general stability is compatible with the duration of the procedure and the biological requirements for immediate functional rehabilitation (25,26).

In the extraoral physical examination, the analysis of smile dynamics is a cornerstone of reverse planning, encompassing the assessment of the smile line, lip support, and the degree of gingival display (5,27). Facial asymmetries, dental midline deviations, and the configuration of the buccal corridors must be carefully documented to support the digital smile design (13,24). This macro-esthetic evaluation provides the necessary coordinates for the virtual positioning of the implants, ensuring that the final prosthesis is in harmony with the patient's facial features (13,26).

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The intraoral examination focuses on soft tissue health, the periodontal phenotype, and the integrity of the remaining alveolar ridge (2). It is imperative that the patient exhibits adequate biofilm control and that active pathologies, such as carious lesions or periodontal diseases, are treated prior to implant placement (1,16).

Cone-Beam Computed Tomography (CBCT)

The integration of Cone-Beam Computed Tomography (CBCT) has fundamentally transformed diagnostic workflows in implant dentistry by delivering comprehensive three-dimensional visualization of anatomical structures, effectively overcoming the inherent spatial limitations of conventional two-dimensional radiography (2,9). This imaging modality enables highly accurate assessment of residual bone volume and the precise localization of critical anatomical landmarks, including the mandibular canal, the nasal cavity, the maxillary sinus, and adjacent roots (10,24). Consequently, preoperative volumetric assessment is essential to thoroughly evaluate bone morphology and determine the necessity of bone augmentation procedures (9,12).

Optimizing CBCT protocols requires a meticulous selection of voxel size and field of view (FOV). Although a 200-µm voxel is generally sufficient for standard implant planning, higher-resolution scans with smaller voxels may be indicated to resolve complex, fine anatomical details (2,18). To minimize patient exposure, radiation dosimetry must adhere strictly to the ALADAIP (As Low As Diagnostically Acceptable, Indication-oriented, and Patient-specific) principle, ensuring the lowest possible dose necessary to achieve diagnostic objectives (2,28). Furthermore, the FOV must be tailored to encompass the region of interest while providing a sufficient number of stable anatomical reference landmarks required for accurate digital registration (2,6).

Post-acquisition processing of CBCT datasets allows for the generation of non-orthogonal, oblique, and curved planar reconstructions, enabling the simulation of panoramic views free from the magnification and distortions characteristic of traditional panoramic radiography (2,29). Clinicians can easily extract serial cross-sectional slices to inspect the prospective surgical site from multiple perspectives, significantly increasing diagnostic accuracy when selecting implant length and diameter (2,6). This multiplanar visualization capacity serves as a prerequisite for predictable virtual treatment planning and is instrumental in minimizing intraoperative surgical morbidity (10,30).

Despite these clinical benefits, CBCT imaging presents distinct challenges, notably the susceptibility to image artifacts caused by patient motion or high-density dental materials (2,10). These artifacts can distort both bone borders and dental surface details, frequently necessitating manual data segmentation to mitigate inaccuracies (10,31). Specifically, scattering from metallic restorations, pre-existing implants, or orthodontic appliances produces severe streaks and "noise" that mask adjacent bone anatomy, representing a primary source of error during the initial dataset alignment (11,12). Additionally, because grayscale values in CBCT are not standardized, traditional Hounsfield units (HU) utilized in medical CT are inapplicable, rendering automated bone density measurements unreliable within virtual planning software (10,29).

CBCT datasets are exported and stored in the universal DICOM (Digital Imaging and Communications in Medicine) format, which preserves crucial geometric metadata and acquisition

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parameters (10,18). Ultimately, these files serve as the foundational "anatomical map" onto which optical surface scans are superimposed to construct a highly accurate, multi-layered "virtual patient" (2,8).

Intraoral Scanning (IOS)

Intraoral scanning (IOS) has established as a foundational technology in digital implant dentistry, allowing for the efficient optical capture of soft tissue topography and teeth (2,13). This digital modality significantly reduces the limitations inherent to conventional physical impressions, such as the volumetric distortions of elastomeric materials and gypsum (15,18). Beyond technical precision, IOS enhances patient comfort by eliminating the risk of nausea and minimizing chairside clinical time (14,15,32).

Scanning devices output digital files in universal formats, such as Standard Tessellation Language (STL) and Polygon File Format (PLY), which serve as the baseline for the digital workflow (2,10). While STL files record only surface geometry, PLY files preserve color and texture details, simplifying the differentiation between teeth, mucosa, and pre-existing restorations (10,12). Integrating these datasets allows clinicians to export information to various planning software packages and prosthetic laboratories (7,10,12).

In the surgical phase, transferring the position and inclination of implants to the virtual environment is achieved using devices screwed onto the implants or abutments, enabling the software to identify the precise three-dimensional location of the prosthetic connection (21,30,33). The use of customized scan bodies or "individualization" techniques has been described to faithfully capture the emergence profile, ensuring superior esthetic outcomes in the final rehabilitation (14,34,35).

To optimize registration fidelity on abutment teeth, techniques such as "cut out-rescan" are applied, allowing operators to erase areas of inaccuracy and rescan only the cervical margin after gingival retraction (14,36). This digital refinement ensures that the marginal adaptation of crowns on implants and natural teeth is equivalent or superior to analog methods (14,18). The ability to superimpose pre- and postoperative scans also facilitates the monitoring of volumetric changes in peri-implant tissues over time (14,15,37).

In complex cases, such as full-arch rehabilitations, IOS can be integrated with complementary technologies, including photogrammetry and facial scanning (15,6). Photogrammetry (e.g., ICam4D) is particularly useful for determining the relative position of multiple implants with high accuracy, overcoming the cumulative error limitations of IOS in edentulous arches (15,6). Fusing these datasets with facial scanning enables the construction of a complete "virtual patient", in which active smile dynamics guide the prosthetically driven implant positioning (13,15,24).

Complementary and Digital Records

Although CBCT and intraoral scanning represent the fundamental pillars of digital dentistry, incorporating complementary records is essential for constructing a reliable "virtual patient", particularly in highly complex rehabilitations (2,13). Conventional 2D photography remains a primary tool for macro-esthetic analysis, enabling a thorough evaluation of the smile line, lip support at rest, and buccal corridor configuration (13,24,26). However, the advancement toward 3D facial scanning allows for capturing

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facial volumetrics in a three-dimensional environment, directly integrating facial dynamics into the implant planning coordinate system (2,15,38).

The clinical utility of facial scanners and photogrammetry lies in precisely defining the relative position of multiple implants during full-arch rehabilitations, effectively overcoming the cumulative error limitations associated with intraoral scanning over extended edentulous spans (6,15,24). These systems facilitate the superimposition of smile dynamics and facial soft tissues onto underlying bone and dental models, generating layered datasets that guide prosthetically driven implant positioning (2,15,25). This digital integration assists clinicians in predicting how the prospective restoration will affect the patient's facial profile and subjective satisfaction prior to surgical intervention (13,15,25).

The Digital Smile Design (DSD) protocol serves as an indispensable planning and communication tool, utilizing facial landmarks to guide digital diagnostic waxing and motivational mock-up design (13,39,40). Contemporary planning software incorporates artificial intelligence (AI) algorithms to automatically detect remaining dentition and propose anatomical tooth arrangements that respect facial proportions and the patient's reference lines (6,13,41), thereby reinforcing the reverse planning concept and enhancing treatment predictability (7,21,42).

Beyond esthetic records, mandibular kinetics and dynamic occlusal registration can be digitally captured to ensure functional harmony (2,43). Utilizing digital facebows and data transfer to virtual articulators allows parameters such as the vertical dimension of occlusion (VDO) and excursive guidance to be validated within the software prior to prosthesis fabrication (15,24,43). This step is critical for ensuring the passive fit of CAD-CAM frameworks and long-term occlusal stability, significantly reducing the need for clinical adjustments during the delivery of the definitive prosthesis (5,37,44).

4- DATA INTEGRATION AND VIRTUAL PATIENT CREATION

Data Fusion and Registration (DICOM/STL/PLY)

Three-dimensional data registration is the process of precisely aligning different digital datasets, primarily DICOM files (derived from CBCT) and optical surface scans in STL, PLY, or OBJ formats, within a single three-dimensional coordinate system (2,7). This step is critical because, while CBCT provides high-resolution diagnostic information regarding hard tissues, it exhibits distinct limitations when resolving dental surface details and mucosal contours due to scatter and motion artifacts (10). Optical scans, conversely, capture highly accurate surface geometry and, in the case of PLY files, preserve color and texture metadata that significantly assist in clinical tissue differentiation (10,12). The precise superimposition of these complementary datasets enables a realistic, multi-layered visualization of the residual anatomy and its direct spatial relationship to the prospective prosthetic rehabilitation (5,6).

Within this digital workflow, the planning software establishes a virtual three-dimensional workspace into which the surface scan dataset is registered, utilizing coordinates that typically derive from the actual position of the patient during CBCT acquisition (7,10). Even when this coordinate system is not explicitly selected by the operator, the CBCT coordinate frame acts as the default geometric reference for the final alignment (6,7). This integration successfully culminates in the construction of the

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"virtual patient," a composite of superimposed image layers that facilitates a backward, prosthetically driven diagnostic analysis guided entirely by the planned esthetic and functional outcome (2,21).

Alignment techniques vary from the manual selection of matching anatomical landmarks or identical fiducial points—typically requiring at least three distinct references, such as stable fissures or cusp tips—to the utilization of radiographic templates containing specific indexing markers (18,24). In completely edentulous patients, where stable anatomical tooth landmarks are absent, radiopaque markers temporarily secured to the existing prosthesis or a dedicated bite registration plate are essential to ensure the accuracy of the dataset superimposition (9,45). Furthermore, surface mapping protocols allow for the execution of guided surgery by pairing multiple coordinate points on the surface of digital models with their corresponding anatomical representations in the CBCT scan (10,46).

Contemporary Computer-Aided Design Implant Planning Software (CAD-IPS) increasingly incorporates artificial intelligence (AI) algorithms to automate both the segmentation and registration processes (13,47). These AI tools can automatically detect remaining dentition and superimpose DICOM and STL files without requiring extensive manual intervention, which effectively minimizes inter-operator variability and enhances chairside clinical efficiency (6,41,48). Consequently, this automated approach optimizes interdisciplinary communication and elevates the accuracy of virtual implant positioning by reducing human error during manual point-matching alignment (13,48).

Final validation of the aligned datasets remains a critical clinical landmark, routinely performed via meticulous visual inspection across multiple planes to confirm that the contours of the optical surface scan perfectly coincide with the radiographic boundaries of the tissues (2,45). Registration errors at this stage can compromise the predictability of the entire subsequent digital workflow, directly impacting the clinical accuracy of the manufactured surgical guide (4,7). Therefore, a disciplined removal of CBCT metal artifacts and verifying the passive fit of the virtual templates over the anatomical structures are fundamental prerequisites to guarantee that the virtual plan faithfully represents the actual clinical scenario (10,18).

Virtual Patient Segmentation and Validation

The construction of the virtual patient is consolidated by integrating multiple layers of diagnostic datasets, including CBCT DICOM files, optical surface scans (STL/PLY), and, in complex cases, 3D facial scans (2,38). This multi-layered digital model enables clinicians to visualize the patient's anatomy from diverse perspectives, facilitating a diagnostic analysis that correlates facial esthetic dynamics with residual bone availability (2,21). The fidelity of this virtual patient underpins the predictability of both surgical and prosthetic planning (21,38).

Data segmentation is the technical process of isolating specific anatomical structures—such as individual teeth, bone volume, the maxillary sinuses, and the mandibular canal—to convert them into independent, manipulable 3D objects (2,10). This step allows for the evaluation of hard tissue morphology without the superimposition of other structures, enabling a detailed analysis of the spatial relationships between adjacent roots and critical nerve pathways (10,31).

AI-based tools have optimized segmentation by automating mandibular canal detection and bone cortical boundary delineation with high accuracy (13,41). These algorithms significantly reduce

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manual processing times and inter-operator variability, providing a more standardized anatomical baseline for treatment planning (41,47). Furthermore, automated segmentation of both remaining and missing teeth facilitates the immediate proposal of prosthetic tooth arrangements that respect the biological boundaries of the ridge (13,47).

Consequently, virtual tooth extraction allows clinicians to visualize the morphology of fresh extraction sockets and plan implant placement in a position that optimizes the emergence profile of the prospective prosthesis (2,13). Such manipulations are fundamental for immediate loading workflows, where the provisional prosthesis is designed on the segmented model prior to the actual surgical procedure (13,49).

Validation of the virtual patient is an indispensable clinical step that involves verifying registration and segmentation accuracy through visual inspection tools (45,46). Features such as "check alignment" allow operators to confirm that the intraoral scan contours perfectly coincide with the radiographic surfaces of teeth and bone, often employing distinct colors for each layer (6,46). Any discrepancy identified during this phase—such as deviations between virtual and actual occlusal surfaces—necessitates restarting the alignment process to prevent cascading errors in the final surgical guide (6,45).

The safety of the entire computer-assisted surgery workflow relies on the geometric integrity of this validated model, which must accurately reflect the intraoral clinical scenario (4,18). Target registration errors (TRE) can occur if segmentation fails to capture stable anatomical landmarks or if original datasets contain distortions (4,7). Mastering the segmentation and validation stages therefore ensures that the virtual plan is translated into faithful surgical execution, minimizing the risk of damage to vital structures (7,18).

5- COMPUTER-AIDED TREATMENT PLANNING AND PROSTHETIC CAD DESIGN

Reverse Prosthodontic Planning

Reverse prosthodontic planning represents a fundamental paradigm shift in contemporary implant dentistry, establishing the design of the prospective prosthesis as the starting point for all therapeutic interventions (7,9,50). Unlike conventional approaches driven exclusively by residual bone availability, the integrated digital workflow allows esthetic, functional, and biological requirements to dictate the optimal three-dimensional position of the implants (2,7,51). This strategy ensures that the implant system is designed by considering the dynamic interaction among the restoration, the implant supracrestal complex, and the surrounding peri-implant tissues (2,9,51).

The initial step involves creating a **digital diagnostic waxing or virtual set-up**, strictly guided by occlusal parameters, phonetics, and the patient's esthetic expectations (2,13,49). Using CAD design software, clinicians can project the final dental morphology onto the virtual arch models, harmonizing the smile with the facial dynamics captured via photographs or 3D facial scans (5,13,39). This prospective restoration serves as the spatial blueprint that defines the necessary coordinates to guide the subsequent osteotomy and implant placement phases (2,5,25).

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Planning the **implant supracrestal complex**—the transmucosal component of the system—is essential for designing the emergence profile (2,31,51). The virtual design of this region allows clinicians to anticipate the support required for the soft tissues, aiming to replicate natural tooth anatomy and prevent esthetic or biological complications arising from compromised restoration designs (2,34,52). This approach optimizes the implant-abutment-crown interface during the design phase, promoting long-term volumetric stability and the health of peri-implant tissues (2,31,53).

The visualization provided by prosthetically driven planning facilitates interdisciplinary communication and simplifies obtaining patient informed consent (13,21,54). Utilizing tools such as digital smile design (DSD) and fabricating intraoral mock-ups allow the planned outcomes to be clinically validated in the mouth prior to any invasive surgical intervention (21,24,39).

Within computer-aided design implant planning software (CAD-IPS), the virtual prosthetic envelope is superimposed onto the CBCT anatomical dataset, simulating the implant position that best supports the planned occlusal loading (7,8,9). Consequently, this seamless integration—where the crown guides the implant positioning—defines excellence in computer-assisted surgery (7,8,55). This integrated analysis ensures that the implant is placed respecting safety margins relative to adjacent roots and vital anatomical structures without compromising the prosthodontic outcome (8,9,28).

Reverse planning is crucial to minimize future mechanical and biological failures resulting from malpositioned implants (9,56,57). Implants placed solely where bone is available, without restorative considerations, frequently result in oral hygiene difficulties, compromised emergence profiles, and detrimental biomechanical overload (9,46,58). By working backward from the ideal final outcome, the clinician can identify the need for bone or soft-tissue augmentation procedures early in the planning stage to render the planned restoration feasible (9,46,56).

Accordingly, the clinical-laboratory workflow guidelines extend from planning guided bone reduction to the pre-operative fabrication of immediate provisional prostheses (2,5,44). Subordinating the surgical phase to the restorative design has consolidated digital implant dentistry as a discipline centered on biorestorative precision and patient functional satisfaction (2,4,59).

Virtual Implant Positioning

Virtual implant placement represents the core stage of computer-aided implant planning (CAD-IPS), where anatomical and prosthetic datasets are harmonized in a three-dimensional environment (2,10). This step transcends a simple search for available bone volume, focusing instead on designing an integrated system that ensures biomechanical longevity and the long-term health of peri-implant tissues (4,51).

Selecting the implant type, diameter, and length is determined by the requirements of the planned superstructure and visualized anatomical constraints (10,14). The clinician must establish an insertion axis that best aligns with the prosthetic design, aiming for a natural emergence profile and favorable occlusal load distribution (30,49). Manufacturer-provided digital implant libraries ensure that virtual dimensions correspond precisely to the actual fixtures to be placed, enabling the simulation of theoretical primary stability (2,6).

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Strict biological parameters guide implant positioning, such as maintaining a minimum buccal bone wall thickness of 2 mm to prevent dehiscence and mucosal recession (2,30). Regarding depth, positioning the implant platform 3 to 4 mm apical to the prospective restorative zenith is recommended to optimize the supracrestal biological space (30,51).

Surgical safety is enhanced by the planning software's capacity to delineate exclusion zones and visualize critical anatomical landmarks, such as the mandibular canal, nasal cavity, and maxillary sinus (2,9). Multiplanar inspection tools—including curved and cross-sectional reconstructions—allow clinicians to verify the implant's proximity to adjacent teeth and roots (10,12).

Interaction within the virtual environment is facilitated by intuitive translation, rotation, and tilting tools, which allow for the refinement of implant positioning from various clinical perspectives (10,46). Simultaneous visualization of the digital diagnostic waxing and the bone volume enables fine angular adjustments, ensuring that the prospective screw-access hole is located in non-esthetic zones (2,49). This multi-layered analysis reduces reliance on operator intuition, standardizing planning accuracy across diverse clinical scenarios (6,9).

Artificial intelligence (AI) can also perform automated prediction of implant positioning based on deep learning algorithms trained on large diagnostic datasets (41,47), instantaneously suggesting optimized placements that balance bone availability with ideal prosthetic trajectories (41,48). While the final clinical decision remains with the practitioner, AI serves as a powerful utility to increase efficiency and mitigate human error during treatment plan design (13,47).

Consolidating the virtual position culminates in validating the "patient-optimized" or bio-restorative implant position, which fully satisfies biological, mechanical, and functional requirements (7,51). This simulation phase enables early identification of the need for bone augmentation or sinus floor elevation before executing the case clinically (9,12). Once validated, the planned implant position serves as the immutable geometric baseline for designing CAD/CAM surgical guides or programming dynamic navigation systems (2,4).

Surgical Guide Design (CAD)

The computer-aided design (CAD) of a surgical guide represents the transition from virtual planning to a physical device capable of transferring three-dimensional implant coordinates directly to the surgical site (2,9). This step is executed within specialized computer-aided design implant planning software (CAD-IPS), where the clinician outlines the guide geometry over the patient's digital model once the optimal implant position has been established (9,23). Final design validation is crucial to confirm adherence to the reverse planning strategy, ensuring that both the entry point and drilling trajectory precisely reproduce the planned restorative layout (2,9,21).

During the CAD phase, selecting the guide support mechanism—whether tooth-, mucosa-, bone-supported, or hybrid—is dictated by the specific anatomical characteristics of the surgical site (2,10). For partially edentulous arches, tooth-supported guides are typically preferred due to their superior stability and seating accuracy (7,18). Technical parameters, including guide thickness—commonly set at 3 mm to prevent mechanical deflection—the extension of the bearing surface, and the

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incorporation of buccal inspection windows, are defined within the software to facilitate visual verification of stable, passive seating during the surgical procedure (2,18,19).

Designing the guide holes requires choosing between sleeve-incorporated (metal sleeve) and sleeveless configurations, which interface directly with guided drills or drilling keys (4,7). Open-sleeve designs can be selected for posterior regions with restricted interocclusal space, allowing for lateral drill insertion (7,9). Consequently, the vertical distance from the apical end of the sleeve to the bone crest (sleeve offset) is meticulously calculated in the CAD software to ensure that the drilling sequence reaches the pre-planned depth without axial deviations (4,7,10).

For complex full-arch rehabilitations, the CAD workflow may involve designing stackable surgical guides, which utilize sequential, interlocking layers to coordinate bone reduction, implant placement, and immediate provisional prosthesis positioning (26,44). These integrated, multi-piece templates rely on bone anchor pins and mechanical or magnetic locks to completely eliminate micromovements during the surgical procedure (7,26). Recent innovations also permit the integration of internal irrigation channels directly within the surgical guide design, optimizing cooling of the drill to prevent thermal damage during high-precision flapless osteotomies (44,45).

6- TRANSFER TO THE SURGICAL FIELD (CAM) AND CLINICAL EXECUTION

Fabrication and Clinical Validation of the Surgical Guide

The physical fabrication of the surgical template is executed using CAD-CAM workflows, which can be categorized into either additive manufacturing (3D printing) or subtractive methods (milling) (2,60). In additive manufacturing, technologies such as Digital Light Processing (DLP) utilize certified biocompatible resins to produce highly accurate structures at a fraction of the operating costs associated with traditional laboratory methods (4,60). Conversely, subtractive milling utilizes pre-polymerized polymethyl methacrylate (PMMA) blanks, which inherently provide excellent structural integrity and high resistance to mechanical deformation (40,60). While comparative literature indicates that both techniques deliver clinically acceptable levels of dimensional accuracy, 3D printing has emerged as the preferred clinical option owing to its rapid production cycles and minimal material waste (4,61).

Following fabrication, strict post-processing protocols are mandatory to verify the device's clinical safety and structural integrity. This phase involves thorough washing in isopropyl alcohol to remove unpolymerized monomer residues, followed by final photopolymerization in ultraviolet (UV) curing chambers to optimize both mechanical properties and resin biocompatibility (4,60). Guiding accuracy is conventionally achieved by incorporating metallic sleeves into the guide holes to stabilize the drill sequence; however, contemporary sleeveless guide designs can also be planned to interface directly with specialized guided surgery keys or drill shanks (2,10). To mitigate any dimensional variations that could compromise intraoperative trueness, clinicians and technicians must strictly adhere to printer calibration protocols and respect the minimum recommended material thickness during the CAD phase (4,10,60).

Clinical validation is the final quality gate prior to patient treatment, consisting of a rigorous intraoral evaluation of the guide's seating, stability, and passive fit (24,49). Visual inspection is facilitated

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by incorporating open viewing windows into the vestibular aspect of the CAD design. This allows the surgeon to confirm complete, intimate adaptation against the respective bearing surface, whether tooth-, mucosa-, or bone-supported (2,18). Only after this meticulous validation is completed can the virtual implant coordinates be deemed safely and predictably transferred to the actual surgical site (2,12).

Before beginning any surgical procedure, strict adherence to asepsis protocols for the surgical templates is important, regardless of the specific surgical technique chosen. Microbiological control must be performed using disinfection methods that preserve the guide's dimensional stability across all spatial planes. For chairside clinical applications, cold chemical sterilization via immersion in a 2% chlorhexidine digluconate aqueous solution for an evidence-based, clinically effective duration is highly recommended to ensure adequate disinfection without inducing material distortion.

Static Computer-Assisted Implant Surgery (s-CAIS)

Static computer-assisted implant surgery (s-CAIS) is defined as the utilization of digital technologies and software to plan a patient-optimized three-dimensional implant position, followed by the use of CAD-CAM manufactured surgical templates to guide the osteotomy and final fixture placement (4,7). Although emerging technologies such as dynamic navigation and robotics have entered the clinical landscape, static templates remain the dominant modality for guided implant placement in contemporary practice (2,4). The s-CAIS workflow enables a faithful transfer of the virtual treatment plan to the surgical site, reducing the clinician's reliance on subjective visual estimation and standardizing clinical outcomes (4,9).

Clinical execution of s-CAIS requires system-specific guided implant surgery kits (GISKs), which incorporate drills with physical depth limiters (stops) and guiding keys or handles that interface with the guide sleeves (4,7). These sleeves, which may be fabricated from metal, PEEK, or zirconia, guide the surgical drills with precise mechanical tolerances, minimizing intraoperative vibration and axial deviations (4,7,9). In posterior regions characterized by restricted mouth opening, open-sleeve designs can be planned to allow lateral instrument access, successfully overcoming the spatial constraints typical of conventional closed-sleeve guides (9,7,62).

A major advantage of s-CAIS is that it facilitates minimally invasive procedures, such as the flapless technique, which avoids the elevation of mucoperiosteal flaps (12,22,23,63), thereby fully preserving the intimate relationship between the periosteum and the alveolar bone surface while maintaining optimal vascularity. This approach significantly reduces transoperative hemorrhage, chairside time, and postoperative patient discomfort, while encouraging faster soft tissue healing (4,22,23,44). Additionally, the high positioning accuracy supports the predictable execution of immediate loading protocols, where prefabricated provisional prostheses can be delivered with minimal adjustments immediately following surgery (6,18,49). It is worth noting, however, that s-CAIS is fundamentally a spatial coordinate transfer tool rather than an inherently flapless surgical technique.

Comparative studies demonstrate that s-CAIS provides superior accuracy over freehand implant placement, yielding significantly lower global deviations at both the implant platform and apex (4,18,19). Nonetheless, the literature emphasizes that static guides limit the operator's tactile proprioception and direct visualization of the underlying bone anatomy, which may present a

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disadvantage for trainees in the early stages of their learning curve (4,19). Furthermore, s-CAIS is a rigid system that precludes any intraoperative modifications to the planned implant position; should any guide seating error occur, the integrity of the entire virtual plan is compromised (6,12,16).

The cost-benefit ratio of the static technique remains widely discussed. Evidence indicates that despite the upfront financial investments in software licensing and template manufacturing, the reduction in active surgical time and the mitigation of severe complications justify its adoption in highly complex cases (2,4). In-office 3D printing systems have rendered s-CAIS increasingly accessible and efficient, enabling clinicians to control every phase of guide fabrication (4,60). However, the practitioner must possess a thorough mastery of biological and biomechanical principles, as the technology must serve as an adjunctive utility rather than a substitute for critical clinical judgment (4,16).

In conclusion, s-CAIS has established itself as a cornerstone of digital implant dentistry by offering predictability and safety, particularly in extensive rehabilitations and highly demanding esthetic zones (2,4,49). The future of this technique lies in refining hardware components and integrating artificial intelligence algorithms to optimize guide design while further minimizing cumulative workflow errors (2,13).

Dynamic Navigation (d-CAIS) and Mixed Reality

Dynamic computer-assisted implant surgery (d-CAIS), often termed navigated surgery, relies on optical tracking systems to provide real-time guidance during surgical instrumentation (2,9). By utilizing sensors secured to both the surgical handpiece and the patient's anatomy, stereoscopic cameras triangulate coordinate positions, projecting the exact drill location onto a pre-acquired CBCT 'anatomical map' (2,6). This technology enables clinicians to monitor osteotomy progression relative to critical landmarks and the planned prosthetic layout without the spatial constraints of a physical template (2,9).

A primary distinction between d-CAIS and static techniques is intraoperative flexibility, which allows for real-time adjustments to implant position, angulation, and depth mid-procedure (6,16). Because navigated systems eliminate physical templates that obstruct the surgical field, they enhance direct visualization, permit uncompromised site irrigation, and preserve the operator’s tactile proprioception (6,4). Moreover, dynamic navigation bypasses the spatial barriers encountered in patients with restricted mouth opening, where physical guides and static sleeves are often clinically unfeasible (7,9).

Regarding accuracy, current evidence suggests that dynamic navigation outperforms freehand techniques and achieves outcomes comparable to static guided surgery, particularly in controlling angular deviation (16,19). Clinical follow-up studies demonstrate that navigated workflows are highly reliable for full-arch rehabilitations involving immediate loading, ensuring implant placement with minimal deviations from the planned coordinates (6,5). However, achieving this precision depends on a rigorous calibration and registration protocol to maintain spatial fidelity between the virtual environment and the active operatory field (7,9).

Integrating Mixed Reality (MR) represents a technological leap, overlaying high-definition 3D planning holograms directly onto the surgeon's field of view via head-mounted displays such as the

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HoloLens 2 (12,12). In mixed reality-based dynamic navigation (MR-DN), the clinician views planned trajectories, adjacent teeth, and projected anatomical boundaries superimposed on the patient, eliminating the need to look away toward external screens (11,12). This immersive approach offers a more intuitive, ergonomic workflow that mitigates the mental fatigue associated with hand-eye-screen coordination (11,12).

Despite this innovative potential, dynamic workflows and mixed reality still present challenges, including high implementation costs and a demanding technical learning curve (16,19). The future evolution of these modalities lies in their convergence with AI to automate dataset registration and simplify instrument calibration independently of physical markers (13,41).

7- RESTORATIVE PHASE AND FINAL REHABILITATION

Provisionalization and Immediate Loading

Immediate loading is defined as the placement of an implant-supported prosthesis within 48 hours of surgical intervention (22,23). This protocol offers significant clinical and psychosocial benefits, including the immediate restoration of esthetics and function, improved patient satisfaction, and the elimination of a temporary edentulous phase during initial healing (5,30). Furthermore, immediate provisionalization helps preserve alveolar bone volume and soft-tissue architecture by guiding the development of the emergence profile and maintaining the interdental papillae (5,26,42).

Achieving adequate primary stability is a strict prerequisite for immediate loading, necessitating high insertion torque values during placement (26,49,64). If sufficient primary stability is not attained, the implant must be excluded from the immediate loading protocol to safeguard osseointegration (49). Moreover, the design of provisional restorations in the esthetic zone must adhere to bio-restorative principles—specifically contouring the emergence profile to support the gingival architecture—while remaining completely out of occlusion, with no contact during centric occlusion or eccentric excursions, to prevent premature mechanical overload (64,65).

In contemporary digital workflows, provisionalization is streamlined by CAD-CAM technologies, which enable the design and fabrication of crowns or full-arch prostheses prior to surgery (4,49). High-density polymers, such as polymethyl methacrylate (PMMA) and composite resin-based materials, are preferred for their superior mechanical strength, color stability, and biocompatibility compared to conventional self-curing resins (30,44,49). These restorations are typically pick-up relined chairside, utilizing components such as temporary titanium cylinders and low-shrinkage resins to accurately register the intraoral implant positions (5,26,49).

Protocols such as the digital "All-on-4" concept demonstrate high predictability and fidelity between virtual planning and clinical execution, ensuring a passive fit of the framework while minimizing complex post-surgical occlusal adjustments (6,25,44). Thus, immediate digital provisionalization not only satisfies immediate functional demands but also serves as a vital diagnostic utility to validate esthetic and phonetic parameters prior to fabricating the definitive monolithic zirconia or ceramic prosthesis (5,42,30).

Post-Surgical Scanning and Digital Transfer

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Following implant placement, transferring three-dimensional coordinates to the digital environment is achieved using IOS and transfer components, such as scan bodies (30,33). These components are secured onto the implant platform or the intermediate abutment, enabling the planning software to precisely identify implant position, angulation, and depth relative to adjacent teeth and surrounding soft tissues (7,12,33). This digital registration eliminates the inaccuracies inherent to conventional physical impressions, delivering a high-fidelity virtual model that serves as the foundation for designing customized abutments and definitive restorations (21,33).

In full-arch rehabilitations, the reverse scanning technique integrates occlusal records and implant coordinates by combining intraoral scans of the provisional prosthesis *in situ* with extraoral scanning of implant analogs, thereby enhancing the precision of the definitive prosthesis (5). Furthermore, complementary technologies such as photogrammetry can be integrated into the post-surgical workflow to determine the relative positions of multiple implants with superior accuracy compared to conventional IOS over extended edentulous spans (6,15).

The post-surgical scanning phase also plays a crucial role in validating surgical execution, allowing clinicians to superimpose the actual postoperative implant position onto the initial virtual plan to evaluate positional deviations (12,45). Digital tools, such as the "cut out-rescan" function, assist in refining the registration of cervical margins and hard-to-capture areas, ensuring superior marginal adaptation of milled superstructures (14,36). Once the digital model is validated, files in universal formats like STL or PLY are exported to production centers, where CAD-CAM technologies fabricate the prosthetic components with high micrometric precision (10,30,33).

Custom Abutments and CAD Design

The integration of CAD-CAM systems in implant dentistry has opened new avenues for fabricating customized restorative solutions tailored to each patient's specific anatomical requirements (30,33). Computer-aided design (CAD) enables clinicians and laboratory technicians to design abutments that replicate the exact three-dimensional position of the implant, successfully overcoming the geometric and esthetic limitations of conventional prefabricated components (10,33). This technology's widespread adoption stems from its ability to yield a more streamlined, predictable workflow, allowing the visualization of the prospective rehabilitation in relation to the surrounding soft tissues prior to physical manufacturing (33,37).

The fabrication workflow begins with digital data acquisition, which is then processed to generate a customized virtual model that allows for precise adjustments to the emergence profile and the trajectory of the screw-access hole (31,33). Real-time visual analysis within the CAD environment reduces laboratory errors and optimizes chairside time during the subsequent restorative phase (33,37).

A vital component of the CAD phase is the customized configuration of the supracrestal tissue complex to promote biological stability and esthetic harmony (2,31). The design software facilitates the division of the emergence profile into critical and subcritical zones, where the morphology can be contoured to support the soft tissues without compromising local vascularity (31,51). By leveraging mirroring tools from the contralateral homonymous dentition, the clinician can design custom abutments

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that mimic natural tooth anatomy, encouraging papilla development and seamless gingival integration (31,13).

Regarding restorative materials, the CAD-CAM workflow accommodates high-performance substrates, including titanium blanks or monolithic zirconia, processed via computerized milling (30,33). Hybrid configurations—combining a customized abutment cemented onto a prefabricated titanium base (Ti-Base)—are frequently utilized to achieve micrometer-level precision at the implant interface (13,31). This technique secures the mechanical stability of the assembly while mitigating the risk of biological complications, such as dehiscence, stemming from imprecise marginal adaptation (33,34).

CAD-designed custom abutments are essential for resolving complex clinical challenges, such as managing implants placed in compromised positions or unfavorable inclinations (33,66). The technology can correct severe angulations that prefabricated commercial abutments cannot accommodate, ensuring adequate ceramic thickness and facilitating optimal patient plaque control (33,66). For extensive reconstructions or full-arch rehabilitations, the CAD design of custom multi-unit abutments guarantees a passive fit of the superstructures and balanced occlusal load distribution (44,66).

Definitive esthetic predictability is significantly enhanced by integrating provisional restoration contours into the design software (34,37). Scanning protocols that capture the conditioned emergence profile enable the definitive abutment design to faithfully replicate a clinically validated, functional prototype (34,37). This reduces the need for time-consuming intraoral adjustments and ensures that the transition from the implant fixture to the final restoration is biologically respectful (31,37).

Consequently, mastering CAD design utilities has established itself as a vital prerequisite for achieving clinical excellence in implant-supported oral rehabilitation within the digital era (2,33).

Definitive Prosthesis

The placement of the definitive prosthesis represents the final milestone of an integrated digital workflow, aimed at consolidating the esthetic and functional outcomes planned from the very beginning of treatment. High-performance materials, such as CAD-CAM-milled monolithic zirconia, are widely utilized due to their excellent mechanical strength and optical properties that seamlessly mimic natural dentition (67). The micrometer-level precision achieved by computerized milling facilitates an exceptional marginal fit, which significantly lowers the risk of biological complications compared to conventional analog methods (68). Clinical studies indicate that definitive rehabilitations executed via this digital protocol demonstrate high predictability and outstanding long-term survival rates (69).

Faithfully capturing the emergence profile—previously conditioned by the provisional restoration—is a vital prerequisite for maintaining peri-implant tissue health and papillary stability (31). Applying transfer scanning techniques or digitally duplicating the provisional crown allows the dental laboratory to replicate the matured gingival architecture precisely in the final design (34,37). This model-free workflow optimizes chairside time while eliminating the volumetric distortions inherent to physical impression materials and gypsum (70).

In complex full-arch rehabilitations, fabricating metallic or ceramic frameworks using CAD-CAM technologies is essential to guarantee passive seating over the implants (44). Utilizing milled titanium

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bars or those produced via selective laser melting (SLM) ensures the precise fit required over multiple intermediate abutments, preventing mechanical failures such as screw loosening or prosthetic screw fracture (71,72). Furthermore, preoperative digital validation of parameters like the vertical dimension of occlusion (VDO) and centric relation directly supports functional stability and patient masticatory comfort (5,43).

Additive manufacturing has substantially expanded the boundaries of the restorative phase through the production of high-precision, biocompatible prototypes and components. The interface between these printed materials and the oral environment remains a critical factor for clinical longevity. Strictly controlling surface roughness and surface free energy in these printed substrates is fundamental to mitigate pathogenic colonization and preserve soft tissue integrity; hence, polymer selection in the digital workflow must balance mechanical strength, biocompatibility, and bioactivity (73).

The operational efficiency of a fully digital workflow during prosthetic finalization dramatically reduces the number of patient visits while enhancing subjective patient satisfaction (13,25). Storing the complete digital dataset enables exact replication of the definitive restoration if replacement is required in the future, providing enhanced security and convenience for both clinician and patient (33). Ultimately, the definitive prosthesis represents the culmination of an integrated, highly reliable planning workflow centered on biorestorative excellence and long-term durability in digital oral rehabilitation (31,74).

8- DISCUSSION

The core value of digital implantology extends beyond the mere integration of advanced imaging and virtual planning; its true strength lies in the controlled translation of prosthetic goals into precise surgical execution. Nevertheless, the transition to this digital paradigm is underpinned by a body of literature where the majority of current evidence remains concentrated on preliminary technical and diagnostic validation studies (41). While systematic reviews and meta-analyses consistently confirm the superior accuracy of computer-assisted protocols, translating these findings into tangible clinical benefits requires caution, as geometric precision does not automatically yield superior long-term implant survival rates (4,55).

Comparing static s-CAIS) and dynamic d-CAIS highlights distinct technical and operational constraints that guide clinical decision-making. While s-CAIS is constrained by the inherent mechanical tolerances between the drill and the guide sleeve, as well as the requirement for a significant mouth opening—often exceeding 50 mm (7,19)—d-CAIS demands complex hand-eye-screen coordination as the surgeon shifts focus between the surgical field and the monitor (6). Research indicates that although d-CAIS can provide more refined control over angular deviation by facilitating real-time intraoperative adjustments, s-CAIS remains the dominant modality in daily practice due to its flatter learning curve and less complex hardware infrastructure (4).

Cost-effectiveness analysis suggests that the substantial initial investment required for intraoral scanners, CBCT units, and software licenses remains a major barrier to the universal adoption of this technology. Research indicates that although active surgical duration decreases, the time dedicated to virtual planning increases indirect operating costs (4). However, in highly complex clinical scenarios,

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such as full-arch reconstructions or immediate loading in esthetic zones, the reduction in remakes and the opportunity to utilize stock prosthetic components—thereby avoiding more costly customized alternatives—can financially offset the digital workflow (5,44).

The clinical applicability of digital workflows outside of highly integrated centers depends heavily on the democratization of open-architecture systems and the viability of decentralized production models. Utilizing platforms that support universal STL file export alongside outsourced planning services allows clinicians lacking a heavy in-house digital infrastructure to access the benefits of guided surgery (2,10). Nonetheless, this reliance on external services requires the surgeon to maintain the technical competency necessary to validate the received designs, to avoid the risk of transferring data registration or segmentation errors directly into the active surgical field (24).

Operator-related biases and the intrinsic limitations of software platforms are frequently underestimated in routine practice. Even when working with highly accurate three-dimensional datasets, defining the 'ideal' implant position exhibits significant variability; evidence demonstrates that angular and linear deviations occur even when the same operator plans the identical case at different time points (75). Furthermore, the presence of CBCT metal artifacts and the inaccuracies of automated segmentation algorithms can introduce cumulative errors that compromise the passive fit of the final prosthesis (9,10). Noisy datasets hinder the identification of stable anatomical reference landmarks, compromising the precision of DICOM-to-STL alignment, which directly impacts both final prosthetic passive fit and surgical guide fidelity (9,10). The inaccuracy of segmentation algorithms in noisy images compromises prosthetic passive fit and surgical template fidelity. Therefore, obtaining artifact-free images and performing manual data refinement represent critical steps to mitigate linear and angular deviations during clinical execution (12,13).

Beyond millimetric precision, clinical success relies on the biological integration of materials and the meticulous management of peri-implant soft tissues. The digital workflow minimizes surgical trauma across all cases. This is particularly beneficial for medically compromised patients, who exhibit greater constitutional biological fragility that can lead to increased morbidity due to underlying systemic comorbidities (22,23,49). Long-term tissue stability is further influenced by the mechanical strength and biocompatibility of novel 3D-printed resins (73), as well as the biological efficacy of implant surfaces engineered via selective laser sintering technologies (22,23).

Future trends in digital implant dentistry point toward AI-assisted automation and the implementation of Mixed Reality (MR) to mitigate the visual distraction associated with current dynamic navigation displays. Studies describe the promising potential of robotic systems (r-CAIS) to minimize human variability, achieving submillimetric and near-zero angular deviations (12,16). The technological convergence of automated segmentation algorithms and 3D holographic visualization promises to make prosthetically driven guided planning more intuitive and safer (11,41).

9- FINAL CONSIDERATIONS

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Digital implant dentistry has emerged as a key approach to enhancing therapeutic predictability, seamlessly integrating workflows that span from diagnostic imaging to virtual planning and computer-assisted surgical execution. Adopting prosthetically driven planning ensures that implant placement aligns with the esthetic and functional goals of the rehabilitation, yielding more consistent outcomes even in highly complex clinical scenarios. Clinical evidence suggests that these workflows support adequate clinical stability and help preserve peri-implant tissue health, provided there is strict adherence to patient selection criteria, meticulous technical quality control, and consistent longitudinal follow-up. Furthermore, static and dynamic computer-assisted modalities enhance operating precision and standardize clinical protocols, though they do not replace clinical judgment, operator experience, or fundamental biological and prosthodontic principles.

AI Use Disclosure

Following extensive research, literature review, and critical appraisal of the selected articles, the manuscript was refined with the support of NotebookLM and ChatGPT, under the constant supervision, critical analysis, and final revision of the authors. All conceptual decisions, scientific interpretations, reference selection, methodological frameworks, and the final version of the manuscript remain entirely the responsibility of the authors.

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