

Digital Precision: The role of CAD/CAM in Modern Periodontics

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ABSTRACT:

Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology has revolutionized periodontics by enabling precise planning and fabrication of periodontal prosthesis, surgical guides, and restorative components. This review explores how CAD/CAM systems can be integrated into various periodontal procedures to enhance treatment accuracy, efficiency, and patient outcomes. Digital workflows like virtual modeling and 3D imaging enable highly customized periodontal treatments and minimally invasive surgical procedures. CAD/CAM-fabricated guides contribute to improved accuracy in implant placement and bone regeneration procedures, while digitally designed prosthetics offer superior fit and esthetics compared to traditional methods. Despite these advantages, there are still challenges, such as the high initial cost, need for specialized training, and technical limitations of some materials. Digital dentistry developments are further broadening the use of CAD/CAM in periodontics, offering even more integration in diagnosis, treatment planning, and long-term periodontal health maintenance. This review emphasizes how CAD/CAM is helping to improve periodontal care's accuracy and customization.

Keywords: CAD/CAM, Periodontics, Prosthesis, Guided Tissue Regeneration, GBR.

INTRODUCTION

Technology known as computer-aided design and computer-aided manufacturing (CAD/CAM) has revolutionized dentistry by providing new avenues for accuracy, effectiveness, and patient-centered treatment in a number of dental specialties, including periodontics. CAD/CAM, initially created for the automotive and aerospace sectors in the 1960s, was first applied to dentistry in the 1980s. By facilitating digital workflow and quick in-office production, it completely changed the way dental restorations and prostheses were made^[19,2,30]. CAD/CAM technology's use in dentistry has grown dramatically over the last 20 years. These days, inlays, onlays, crowns, bridges, implant abutments, full-mouth reconstructions, orthodontic appliances, and maxillofacial prostheses all frequently use it^[19,16]. In periodontics, CAD/CAM technology facilitates surgical planning, diagnosis, and the creation of customized parts like periodontal splints, surgical guides, and frameworks for regenerative treatments. The increased precision and repeatability of digital processes can improve outcomes in complex periodontal therapies, minimize

chairside time, and increase overall treatment efficiency^[19,30]. Furthermore, the integration of powerful digital imaging, three-dimensional scanning, and design software improves clinical operations and enables for treatment customization. As CAD/CAM advances, its use promises to improve the quality of periodontal care and support minimally invasive, patient-specific procedures in the future^[19,30].

Diagnostic Applications in Periodontics :

Enhancing accuracy and efficiency in diagnosis, treatment planning, and surgical procedures are the main goals of the diagnostic applications of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) technology in periodontics. Crucial diagnostic applications consist of:

Digital Imaging and 3D Modeling: CAD/CAM incorporates contemporary digital imaging technologies, including intraoral scanners CT scans, and CBCT, to generate precise and in-depth 3D images of the periodontal and dental structures. For the purpose of diagnosis and treatment planning, these pictures allow for the accurate evaluation of soft tissue architecture, bone morphology, and periodontal conditions^[19,2].

Pre-Surgical Planning: By helping to create digital models and virtual treatment plans, CAD/CAM enhances the visualization of the implant and periodontal sites. This enables medical professionals to model various treatment situations and create personalized surgical instruments and prosthetics that precisely match the patient's anatomy ^[37,32].

Guided implant surgery: CAD/CAM allows the creation of guided implant placement templates by integrating CBCT data with intraoral scans. This ensures that implants are positioned optimally in relation to the bone and soft tissue, improving accuracy, cutting down on surgical time, and improving results ^[37,32].

Customized Prosthetics and Surgical Templates: To improve fit, function, and aesthetics in periodontal restorative procedures, highly customized periodontal prostheses, abutments, and surgical guides are designed using CAD/CAM systems on the basis of each patient's unique anatomy ^[19,26].

Improved Patient Education and Communication: Using augmented reality and virtual simulations, practitioners can more effectively explain periodontal diagnoses and treatment plans to patients thanks to CAD/CAM's digital visualization capabilities, increasing comprehension and satisfaction ^[37]. Overall, by utilizing precise manufacturing methods, virtual modeling, and detailed digital imaging, CAD/CAM applications in periodontics enhance patient outcomes, treatment predictability, and diagnostic accuracy.

Surgical applications

The primary surgical applications of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) technology in Periodontics focus on improving the precision, predictability, and efficiency of periodontal and implant procedures. Major uses in surgery include:

Guided Implant Surgery uses CAD/CAM technology to design and create highly precise 3D-printed surgical guides from digital images such as CBCT scans and intraoral scans. These guides facilitate prosthetically-driven implant placement by accurately translating the virtual surgical plan to the actual surgical site, ensuring better positioning relative to bone and soft tissues with minimal deviations. Consequently, this leads to less invasive procedures, shorter surgical times, and improved clinical results.^[21,35,36](Fig.1)

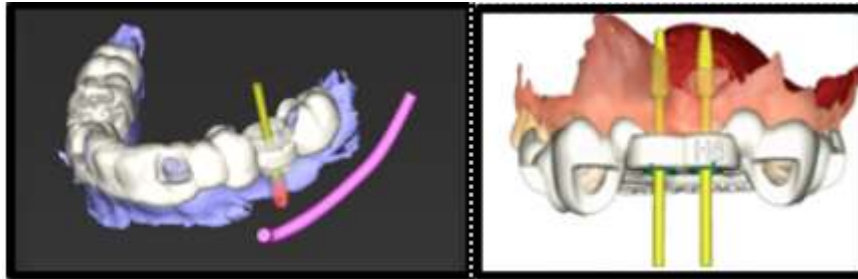


Fig .1 : 1a showing 3D digital model of teeth and gums, used for visualizing dental anatomy and planning treatments. 1b showing An intraoral scanner, which captures digital impressions directly from the patient's mouth to generate the 3D model.

COMPUTER-NAVIGATED STATIC SURGERY

Preoperative digital planning is essential to static computer-assisted implant surgery (sCAIS), where a surgical guide (template) is created using digital imagery and placed rigidly during the procedure [7,39]. It is not possible to alter the implant's location, angulation, or depth during surgery. The drill's course is precisely constrained by these guides, which are held up by teeth, mucosa, or bone. This allows for minimally invasive or flapless installation, which is particularly advantageous in cases where the patient is completely edentulous [39,11]. Although planned and actual implant placements may differ—usually by less than 2.3 mm linearly and 5° angularly—fit precision might be affected by intraoral movement or tissue resilience [7]. According to reports, mistakes may arise from intraoral circumstances, guide stability, or data collecting, and static guides are extremely technique sensitive [7].

COMPUTER-NAVIGATED DYNAMIC SURGERY

Dynamic navigation systems use real-time tracking, usually with stereoscopic cameras or optical markers, to direct implant insertion and osteotomy according to a three-dimensional pre-operative design [10,23]. Dynamic navigation, as opposed to static guidance, enables the surgeon to alter implant position or angulation during surgery by viewing the patient's anatomy and drill trajectory on a monitor [23,24]. This adaptability can be helpful in therapeutic settings that are complicated or unexpected, allowing for modifications for the best results. Studies show that dynamic navigation, particularly when utilizing motion-tracking technologies and high-quality CT-based planning, can reach implant location accuracy on par with static approaches [23].

Virtual Surgical Planning: 3D modelling and diagnostic imaging are combined by CAD/CAM software to create virtual treatment simulations. It enables physicians to preoperatively plan implant positions while taking prosthetic needs and anatomical constraints into account, reducing intraoperative surprises and improving surgical safety and results [21,7]. (Fig.2)

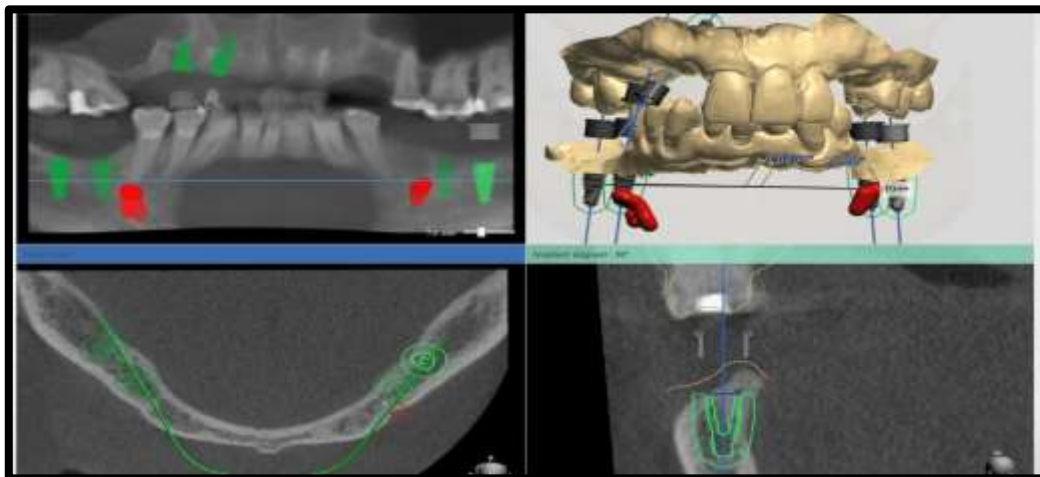


Fig.2 showing virtual surgical planning for dental implants using CAD/CAM.

Custom Surgical Guides: These customized instructions make it easier to perform flapless or minimally invasive procedures, which lessen postoperative discomfort and patient trauma [7,36].

Bone Augmentation Surgery and Complex Cases: CAD/CAM technology helps with the planning and directing of surgeries in difficult situations, like severely atrophic maxillae, facilitating accurate implant placements and bone augmentations that enhance stability and appearance over the long term [8].

Patient-specific prosthetics and immediate loading: By guaranteeing precise implant placement in line with the finished restoration, CAD/CAM enables the creation of surgical guides that correspond with prosthetically-driven implant placements, allowing for immediate or early loading protocols [5].

Enhanced Safety and Efficiency: The use of CAD/CAM surgical guides reduces risks such as nerve injury by limiting deviations from planned implant sites. Though angular and linear deviations up to a few millimeters and degrees are common, careful planning and operator expertise minimize complications [7,36].

REGENERATIVE PERIODONTAL THERAPY

The main component of CAD/CAM-based regenerative periodontal therapy in periodontics is the meticulous design and manufacturing of barrier membranes, bone grafts, and scaffolds to enhance tissue regeneration outcomes.

The regeneration of bone, periodontal ligament (PDL), and cementum can be aided by the creation of patient-specific, 3D-printed bioresorbable scaffolds using CAD/CAM that mimic the natural extracellular matrix and tissue architecture. These scaffolds help cells adhere, proliferate, and differentiate for periodontal restoration [4]. Using CAD/CAM to design and mill customized synthetic bone grafts, such as hydroxyapatite/beta-tricalcium phosphate (HA/beta-TCP) blocks, to precisely fit defect sites 2–3 can improve bone augmentation and implant placement success for alveolar ridge defects.

Guided bone regeneration (GBR) uses titanium meshes made with CAD/CAM technology, which precisely fit the defect area to support and shield graft materials and promote the formation of new bone with the fewest possible complications [27]. Through the creation of allogeneic bone blocks tailored to intricate alveolar ridge defects, CAD/CAM aids in the successful reconstruction of severely atrophic jaws and enhances soft tissue management [38,17]. New techniques that combine CAD/CAM with tissue engineering and cell-based therapies, like cell aggregates and stem cell delivery systems, enhance the functional regeneration of PDL and related tissues.

PROSTHETIC APPLICATIONS POST PERIODONTAL THERAPY:

By facilitating the accurate, individualized, and effective fabrication of dental prostheses, CAD/CAM technology is essential to prosthetic rehabilitation after periodontal therapy. Fabrication of Custom Prostheses: CAD/CAM enables the design and production of extremely precise crowns, bridges, veneers, inlays, onlays, and fixed partial dentures that are suited to the patient's post-therapy periodontal anatomy, guaranteeing the best possible fit and function [26].

Implant-supported prosthetics: It makes it possible to create crowns and implant abutments with precise dimensions and emergence profiles, which enhances load distribution and aesthetic integration in implant dentistry following periodontal therapy [35]. (Fig.3)

Partial and Removable Dentures: CAD/CAM technology is utilized to precisely design and mill partial denture frameworks and removable prostheses from metal alloys or polymers, improving prosthesis stability and patient comfort [35].

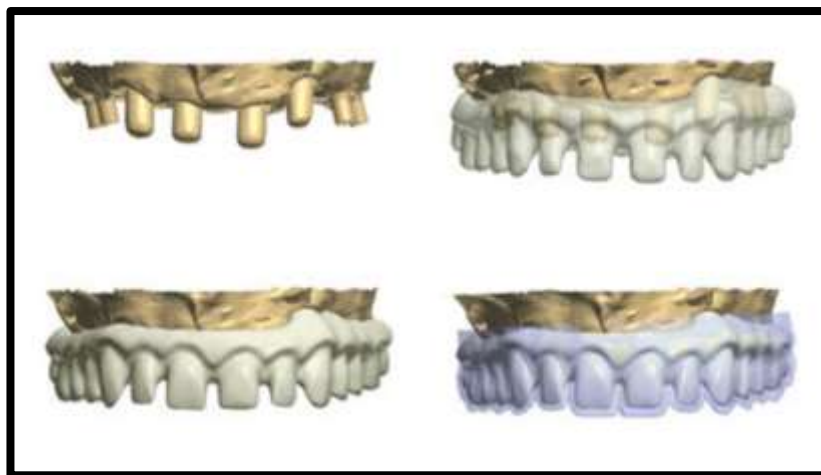


Fig.3 This picture displays digital design models for implant-supported prostheses and denture frameworks using CAD/CAM technology

Enhanced Cooperation and Workflow: Compared to traditional methods, digital impressions and virtual design expedite communication between dental laboratories and clinicians, reducing chair time, speeding up prosthetic production, and minimizing errors [3].

Restoration in both appearance and functionality: When paired with cutting-edge ceramic materials like zirconia and lithium disilicate, CAD/CAM restorations closely resemble the appearance and functionality of natural teeth, enhancing patient satisfaction after periodontal therapy [35].

Periodontal Prosthesis: CAD/CAM helps create retrievable fixed periodontal prostheses, a practical restorative option that is less complicated and more affordable for patients with compromised periodontal support for whom implants are impractical [9].

PERIODONTAL SPLINTS AND OCCLUSAL THERAPY

Periodontal splint and occlusal therapy fabrication and application are greatly enhanced by CAD/CAM technology, which provides better fit, accuracy, and patient comfort.

Periodontal Splints: With the use of CAD/CAM, it is possible to precisely customize thermoplastic or fiber-reinforced composite splints (like polyetheretherketone [PEEK]) to fit the teeth and periodontal stru-

ctures. (Fig.4)

By reallocating occlusal forces, these splints efficiently stabilize movable teeth, enhancing periodontitis patients' comfort and functionality [15]. The digital process improves the splints' durability and appearance while reducing human error.[14]Research indicates that when compared to conventional techniques, CAD/CAM splints fit the dental arch more closely and require less chair time [18]. For patients with compromised periodontal health, materials such as PEEK provide advantageous biomechanical qualities and low plaque affinity [18].

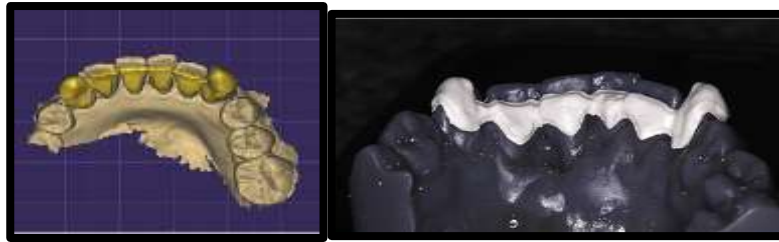


Fig.4 This picture displays CAD/CAM periodontal splints for stabilizing teeth in periodontitis patients.

Occlusal Therapy: To treat occlusal vertical dimension (OVD) and centric relation (CR) problems, CAD/CAM makes it easier to create custom occlusal splints. The functional jaw relationship, occlusal stability, and aesthetics are all improved by the careful design and construction of these splints [6]. Over traditional splints, CAD/CAM occlusal splints offer intraoperative and therapeutic advantages due to their consistency, quantitative control, and manufacturing speed [12]. Splint design changes can facilitate surgical procedures and enhance the evaluation of jaw placement. Additionally, digital workflows enhance the quality of occlusal contact and adjustment efficiency in prosthetic restorations associated with occlusal therapy [13].

ADVANTAGES OF CAD/CAM IN PERIODONTICS

Precision and Accuracy

Compared to conventional techniques, CAD/CAM technology greatly lower the risk of plaque formation and periodontal inflammation by enabling the production of extremely precise restorations with superior marginal adaptability [28,22].Digital impressions improve repair lifetime and fit by removing distortions and irregularities seen in physical impressions [26,22].

Efficiency and Time Savings

The combination of digital scanning, computer-aided design, and automated manufacturing simplifies treatment operations, often allowing for single-visit restorations and reducing the total number of sessions needed[26].This leads to shorter chair time for patients and more productivity for clinicians [29].

Patient Comfort

Digital impressions are non-invasive and do not cause the same discomfort as traditional impression materials, which improves the patient experience and reduces dental anxiety [26]. Minimally invasive preparations leave more of the native tooth and periodontium, which is very beneficial for periodontal patients [26].

Customization and Aesthetics

CAD/CAM allows for a great degree of customization of prosthetic components, delivering restorations

with ideal morphology, color, and shape, providing superior aesthetics and functionality [26,22,29]. The use of biocompatible materials, such as zirconia and lithium disilicate, promotes tissue healing and aesthetics [26,22].

Reduced Human Error and Digital Storage

Automated manufacture reduces manual steps and potential errors, increasing the dependability and reproducibility of prosthetic results [26,29]. All digital records are preserved online for easy retrieval, case review, and patient monitoring [26].

Clinical Benefits for Periodontics

Superior marginal fit reduces plaque retention, promoting healthy periodontal tissues after treatment [28,22]. Faster, less traumatic restorative insertion lowers the risk of soft tissue irritation and contributes to the long-term stability of periodontal treatment sites [26]. Digital workflow improves collaboration between periodontists, prosthodontists, and dental technicians, resulting in better multidisciplinary treatment planning and outcomes [22,29].

LIMITATIONS AND CHALLENGES

Despite being revolutionary in periodontal therapy, CAD/CAM technology has a number of drawbacks and difficulties that affect its widespread application and efficacy:

High Initial Cost: Smaller or less well-funded dental practices may find it difficult to afford the significant initial investment needed to buy and maintain CAD/CAM equipment [26,20].

Learning Curve and Training: Dentists and staff must receive specialized training in order to use CAD/CAM systems effectively. It takes time and work to switch from traditional to digital workflows, which could momentarily impair clinical practice productivity [26].

Technical Problems and Maintenance: CAD/CAM equipment may require routine maintenance and updates, as well as encounter hardware and software errors. These disruptions may cause treatment delays and raise operating expenses [26].

Material Restrictions: While CAD/CAM can work with a wide range of materials, it can be challenging to precisely mill or sculpt certain dental materials. Zirconia and other fully sintered ceramics are more expensive and require more tool wear when milled. Ideal materials for every clinical scenario are also still being developed [26,20].

Occlusal Accuracy Issues: It can occasionally be difficult for existing CAD/CAM systems to accurately reproduce occlusal relationships. To achieve appropriate occlusion and functional load distribution, they might need extra clinical adjustments, particularly in complex cases [3].

Patient and Case Limitations: Even with advancements, not all periodontal or prosthetic cases can be treated equally well by CAD/CAM. Conventional or supplementary methods are still needed for certain complicated pathological or anatomical cases [20].

FUTURE PERSPECTIVE

The future of CAD/CAM technology in periodontal therapy is promising and poised to bring transformative changes through advances in digital design, artificial intelligence (AI), and integration with emerging technologies. Key anticipated developments include:

Integration of Artificial Intelligence: AI will increasingly drive automation and precision in periodontal diagnostics and treatment planning. AI-powered software can analyze radiographs and 3D scans to detect

bone loss, assess tooth prognosis, and optimize surgical and regenerative strategies, improving diagnostic accuracy and clinical decision-making [1,31].

Enhanced Virtual Treatment Planning: Advanced virtual reality (VR) and augmented reality (AR) (Fig.5,6) interfaces are expected to provide immersive digital experiences for clinicians. These tools will facilitate precise planning of complex periodontal surgeries and guided implant placements, enhancing predictability and outcomes [34].



Fig.5 Showing a clinician wearing augmented reality (AR) or VR glasses, visualizing a digital 3D model of a tooth and its internal structures (such as pulp and nerves).



Fig6.6a Surgical guidance using digitized CAD/CAM models for accurate procedures 6b. AR-guided implant sites shown by yellow markers, ensuring precise virtual-to-clinical implant placement.

3D Bioprinting and Customized Biomaterials: Future CAD/CAM applications will expand into 3D bioprinting for fabricating bioactive scaffolds tailored to regenerate periodontal tissues, including bone, ligament, and cementum. This will allow personalized regenerative therapies with improved biological integration [37].

Cloud-Based Collaboration and Digital Workflow Integration: Cloud technologies will enable seamless sharing of digital patient data among dentists, laboratories, and specialists worldwide, accelerating prosthetic fabrication and multi-disciplinary care coordination [1,34].

Remote and Tele dentistry Applications: Digital CAD/CAM data combined with tele dentistry tools will improve remote diagnostics, monitoring, and patient education in periodontal care, increasing access and continuity of care [25].

Improved Materials and Milling Technologies: Continued evolution in CAD/CAM materials-such as advanced ceramics, polymers, and composites-and milling precision will enhance the durability, esthetics,

and biocompatibility of periodontal prostheses and splints ^[19].

CONCLUSION:

By offering precise, effective, and highly customizable solutions that enhance diagnosis, treatment planning, surgical accuracy, regenerative therapy, prosthetic rehabilitation, and occlusal management, CAD/CAM technology has completely transformed periodontics. Physicians can virtually model procedures and view periodontal structures by combining it with state-of-the-art digital imaging and 3D modeling, which enhances predictability and results ^[26]. Furthermore, the use of CAD/CAM supports minimally invasive techniques and fosters streamlined workflows that enhance communication among dental teams and laboratories ^[3].

Continuous technological developments promise to overcome obstacles like high equipment costs, technical learning curves, and material limitations, thereby increasing the capabilities of CAD/CAM. Future developments such as cloud-based collaboration, 3D bioprinting, and AI integration portend a new era of highly effective and individualized periodontal care ^[1,33]. In general, CAD/CAM is a game-changing instrument in contemporary periodontics, greatly advancing clinical effectiveness, improved patient outcomes, and innovative periodontal therapy.

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