

Digitalization in dental implants

**Dr. Rasagna Moola¹, Dr. Monali Patel², Dr. Marjorie Arias Ramirez³,
Dr. Anamika Shrikrishna Deshpande⁴, Dr. Navya Chalamalasetty⁵, Dr. Shalini Boorugu⁶.**

¹BDS, Bangalore, Karnataka, India. rasagnamoola@gmail.com

²BDS, Gujarat, India. monalipatel288@gmail.com

³DMD, Santo Domingo, Dominican Republic. ariasmarjorie2@gmail.com

⁴BDS, MBA, PGDMLE, Maharashtra, India. dranamikadeshpande@gmail.com

⁵BDS, MHI(USA), Vijayawada, India. navyachalamalasetty@my.unt.edu

⁶BDS, Hyderabad, India. shaliniboorgu@gmail.com

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ABSTRACT

This article examines the transformative impact of digitalization on implant dentistry, with a particular focus on technological advancements that have significantly enhanced patient outcomes, treatment precision, and procedural efficiency. Key digital technologies under investigation for their potential to augment diagnostic accuracy and optimize implant placement include intraoral scanners, computer-aided design and manufacturing (CAD/CAM), and cone-beam computed tomography (CBCT). The integration of three-dimensional (3D) printing in implantology is also explored, emphasizing its role in accelerating prosthesis fabrication and streamlining clinical workflows. Additionally, the paper delves into the emerging contributions of robotics and artificial intelligence (AI) in enhancing surgical precision and improving implant success rates. The conclusion provides an outlook on the future trajectory of digital implantology, highlighting ongoing technological innovations that hold promise for further advancements in patient care and clinical outcomes..

Introduction to Dental Implantology

The digitalization of dental implants represents a groundbreaking advancement in dentistry, leveraging state-of-the-art technologies to revolutionize prosthesis fabrication and implant placement. The incorporation of digital tools such as intraoral scanners, computer-aided design and manufacturing (CAD/CAM), and three-dimensional (3D) imaging has significantly enhanced the accuracy and predictability of implant dentistry. These technological innovations enable clinicians to meticulously plan and execute treatments with exceptional precision, ultimately leading to improved patient outcomes.¹

Cone-beam computed tomography (CBCT) has revolutionized implant dentistry by offering highly detailed anatomical insights that aid in precise treatment planning. This advanced imaging technology allows dental professionals to accurately evaluate bone density, angulation, and volume, facilitating optimal implant placement. By delivering a comprehensive 3D view of the oral structures, CBCT minimizes surgical risks and enhances clinical outcomes, ensuring a higher level of precision and patient safety.² The creation of custom prostheses has been made even more efficient by the combination of CBCT and CAD/CAM technology, guaranteeing a perfect fit and better appearance.³

Computer-guided implant surgery exemplifies the transformative impact of digitization on surgical accuracy and efficiency. This approach integrates detailed anatomical data with prosthetic considerations, enabling precise virtual planning of implant placement. Utilizing robotic assistance, navigation systems, or digital templates, the planned procedure is seamlessly translated into the surgical environment. These technological advancements

enhance surgical predictability and patient comfort by significantly reducing operating times while improving overall precision.⁴

Additive manufacturing, commonly known as 3D printing, has significantly advanced digital implant dentistry. By utilizing volumetric 3D imaging data from intraoral scanners or CBCT, clinicians can fabricate highly accurate models and prostheses. This technology enhances patient comfort, streamlines treatment processes, and minimizes material waste. The ability to create detailed anatomical replicas enables a more precise and efficient workflow, ensuring optimal outcomes for both implant placement and prosthetic fabrication.⁵

Robotics and artificial intelligence (AI) are rapidly becoming integral to digital dentistry, offering unprecedented precision and consistency in implant placement. Advanced robotic systems, guided by sophisticated algorithms, can perform complex surgical tasks with minimal human error, ultimately enhancing the overall success of dental implant procedures. The integration of AI into these technologies holds immense potential for improving treatment outcomes and elevating patient satisfaction.⁶

Advanced data integration and imaging techniques are crucial for digital workflows in guided surgery and implant planning. The seamless collaboration between clinicians and technologists is facilitated through the use of Standard Tessellation Language (STL) data and Digital Imaging and Communications in Medicine (DICOM) files. This integration streamlines the backward planning process, allowing for prosthetic-driven implant placement that meets both functional and anatomical needs. As a result, thorough preoperative planning minimizes intraoperative adjustments and enhances the predictability of treatment outcomes.⁷

In conclusion, digitalization has revolutionized implant dentistry by integrating cutting-edge technologies that enhance precision, efficiency, and patient care. The combined use of robotics, artificial intelligence (AI), 3D printing, CAD/CAM, and advanced imaging underscores the transformative potential of digital workflows. As these innovations continue to evolve, they promise to further advance the field, offering patients high-quality, evidence-based treatment solutions with improved predictability and outcomes.

Digital tools for Diagnosis

The digital transformation of implant dentistry is reshaping the field through advancements in equipment, techniques, and clinical protocols, enhancing the overall patient-provider experience. Research indicates that digital diagnostic tools not only expedite procedures but also foster greater trust between patients and clinicians. Moreover, these technologies improve communication between dental professionals and technicians, resulting in streamlined workflows, enhanced treatment outcomes, and increased procedural predictability.

Intraoral Scanning:

Intraoral scanners (IOS) have been utilized for over three decades, with continuous advancements improving their accuracy, reliability, and consistency in delivering high-quality results. These devices play a crucial role in pre-surgical planning by offering detailed three-dimensional imaging that enables clinicians to visualize the clinical scenario with greater clarity. This enhanced visualization allows both dental teams and technicians to identify and address potential adjustments before surgery and subsequent rehabilitation. Furthermore, IOS technology provides significant benefits by reducing time, costs, and the need for physical storage, offering precise digital impressions, customized surgical guides, and secure, easily accessible patient data in digital formats.^{8,9,10}

The accuracy of intraoral scanners is often assessed by repeatedly capturing the same oral structures to evaluate consistency. However, research shows that scanning larger areas can lead to a higher risk of errors, emphasizing the importance of the software used to process and interpret the collected data. As a result, intraoral scanners should be regarded as valuable tools that enhance clinical procedures, rather than as standalone solutions, highlighting the need for careful integration with other technologies and clinical expertise.⁹

CAD/CAM

Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems are essential in digital dentistry, optimizing workflows and enhancing clinical outcomes. These systems consist of three core components: data capture through laser or optical scanning, CAD software for designing restorations, surgical guides, and trays, and CAM technology for fabricating these restorations by shaping materials according to processed digital data. Since their introduction in the 1990s, CAD/CAM systems have revolutionized dental practices by simplifying procedures and improving precision. In contemporary implantology, these systems are extensively used to create customized implant abutments and surgical templates, offering a high level of personalization and accuracy in treatment. An ideal implant abutment replicates the natural tooth structure, preserving the correct morphology and emergence profile to ensure optimal function, aesthetics, and periodontal health. Key steps such as precise implant placement and careful tissue preparation are vital in crafting an abutment that fulfills these goals. CAD/CAM technology facilitates the creation of patient-specific abutments with exceptional accuracy and a consistent fit. However, the technician's expertise is still crucial, as accurate input is necessary for the system to operate effectively. While CAD/CAM systems automate much of the fabrication process, proper training is essential to fully leverage their capabilities. Additionally, these systems can mill various materials, including titanium, titanium alloys, and ceramics, leading to reduced time and cost over the long term.^{11,12}

The use of CAD/CAM surgical guides in implant placement is a highly precise and technique-sensitive process, requiring careful execution of each step before surgery. Essential data from CBCT scans are used to create surgical guides that accurately reflect the planned implant position. This technology helps reduce patient chair time and provides more predictable, less stressful outcomes. However, certain limitations may arise, such as restricted mouth opening, which can impact the guide's design and fit. Additionally, once the surgical guide is fabricated, making adjustments to accommodate unforeseen clinical situations can be challenging.^{8,9}

There are three main types of CAD/CAM surgical guides, each based on their supporting surfaces: **Tooth-Supported Guides**, which rest on the patient's remaining natural teeth and are commonly used when adequate dentition is present; **Mucosa-Supported Guides**, which directly contact the soft tissue and allow for flapless implant placement, offering a more conservative and minimally invasive approach; and **Bone-Supported Guides**, which require a full-thickness mucoperiosteal flap to expose the bone, with the guide placed directly on the bone surface. These are typically used in more complex procedures where visibility and bone modification are necessary. Surgical guides can be created using either the additive stereolithographic (SLA) process or the subtractive milling process, depending on the design generated during planning. By optimizing implant location, angulation, and depth, computer-generated surgical templates significantly enhance placement accuracy, reducing the risk of errors. This technology not only improves the precision of the procedure for dental providers but also leads to better patient outcomes, including reduced intraoperative pain and fewer postoperative complications. Ultimately, it increases patient comfort and helps build trust in the treatment process.⁹ Despite their advantages, clinicians have reported some degree of deviation between the virtual implant plan and the actual guide placement. This discrepancy is influenced by both the software used to create the guide and the operator's expertise. Therefore, proper training in the use of CAD/CAM systems is essential to ensure accuracy and maximize the benefits of this technology in clinical practice.^{9,10,11,12}

Cone Beam Computed Tomography (CBCT)

CBCT has become the cornerstone of implant placement in modern dentistry due to its ability to produce high-quality images with lower radiation exposure for the patient. This imaging modality enables clinicians to thoroughly study a patient's anatomy and create customized surgical protocols. CBCT provides detailed information on bone quality and quantity, the

proximity to critical anatomical structures, and identifies any bony defects or anatomical variations that could impact correct implant placement and subsequent rehabilitation. Its accuracy ensures that implant procedures are more predictable, minimizing potential complications and enhancing treatment outcomes.^{9,10}

Implant planning Software

These programs empower users to thoroughly assess potential implant sites by evaluating critical factors such as bone volume, bone density, available restorative space, and anatomical landmarks. A key advantage is the ability to virtually visualize and position the implant within the proposed site, enabling precise determination of the implant's width, depth, and size before surgery. This capability not only streamlines presurgical planning but also minimizes the risk of implant failure by ensuring optimal placement and reducing the likelihood of complications during the procedure.^{8,9}

Designing and Making Implants

An intraoral scan plays a vital role in the pre-operative diagnosis and treatment planning for static computer-aided implant surgery. When paired with a scan body, it can record the position and timing of dental implants, facilitating the accurate fabrication of the subsequent prosthesis. This approach is more hygienic compared to traditional impressions and offers clinical convenience, especially for patients undergoing orthodontic treatment who already have braces fitted.

The bevel near the occlusal third of the scan body is a crucial design feature for CAD/CAM software to correctly register the implant position and timing. To ensure proper scanning, the scan body should be positioned so that the bevel area is easily accessible for intraoral scanning. Additionally, the distance between implants (in edentulous spaces) can significantly impact the overall accuracy of intraoral scans.

Programs that integrate CBCT image visualization and virtual surgical planning are essential. There are two main types of files used in this process: DICOM files, which assess bone anatomy, and STL files, which are used to perform prosthetic design and fabricate a template for guided surgery.

The method involves obtaining a preoperative CBCT scan (KaVo, Germany) of the patient to gather high-resolution DICOM data for diagnosis and treatment planning. The scanning conditions for the CBCT are as follows: tube voltage of 120 kV, tube current of 5 mA, exposure time of 27 seconds, and a scanning layer thickness of 250 µm. For this procedure, patients with a residual bone height (RBH) of less than 3 mm in the posterior maxillary region are selected for treatment.^{11,12}

An intraoral scan is essential for preoperative diagnosis and treatment planning in static computer-aided implant surgery. When paired with a scan body, it records implant position and timing for prosthesis fabrication. It is more hygienic compared to traditional impressions and offers convenience for orthodontic patients with braces. The bevel near the occlusal third of the scan body is crucial for CAD/CAM software to accurately register implant position. The scan body must be positioned for easy access to this bevel during scanning. Additionally, the distance between implants (edentulous space) can significantly affect the scan's accuracy. Using a model scanner (e.g., D2000; 3Shape), maxillary and mandibular plaster casts are scanned and exported as STL files for further processing.¹³

To create a custom-made implant, register the CBCT data with model scanning data to generate a virtual 3D reconstruction of the patient's bone. Using the 3Shape dental system (3Shape, Denmark), design the implant's position and shape based on the model. The body of the implant should be conically shaped, allowing it to fit securely into the implant hole. Ensure that the lower surface of the wing retention structure precisely fits the outer surface of the alveolar bone. The upper part of the short implant should feature a platform shaped like a frustum of a cone, with a 45° slope and a height of 1 mm. Include an inverted round table hole with a Morse

taper, an inner hexagonal hole, and a threaded hole for fixing the abutment. Design screw hole locations carefully to avoid damaging critical anatomical structures and adjacent healthy teeth.¹³

The CAD workflow for implant planning begins with job definition, where the scope and requirements of the procedure are established. Files, including CBCT (DICOM) and intraoral scans (STL), are uploaded into the CAD software. These files are then cropped to focus on relevant areas, followed by defining the panoramic curve to guide implant positioning. The mental nerve is identified to avoid injury, and a virtual wax-up is created to visualize the final prosthetic design. Image merging, a critical step, combines STL and DICOM files to create a comprehensive 3D model. While some programs offer automatic matching, manual alignment of anatomical points ensures accuracy, making this stage essential for achieving a successful, predictable implant outcome.¹³

The virtual implant plan is then transferred to a manufacturer to fabricate the custom-made implant using a seven-axis lathe (480MT; Willemin). This precise manufacturing process ensures the implant's design matches the virtual specifications. Alongside the implant, a resin surgical template is designed and fabricated to assist in the accurate placement of the implant during surgery. After manufacturing, the custom-made implant is tested for accuracy and fit on a 3D bone reconstruction resin model, ensuring that it aligns properly with the patient's anatomy before proceeding with the surgical procedure. This step helps verify both the implant's functionality and the surgical template's precision for optimal results.^{13,14} CAD-CAM framework materials such as pre-sintered soft alloys, fiber-reinforced composite resins, PEEK, and PEKK in high-performance polymer family, and 4Y-TZP.¹⁴

Out of 885 initially reviewed articles, 5 met the criteria: 3 focused on CAD/CAM frameworks and 2 on CAD/CAM abutments. The clinical trial studies included 189 prostheses supported by 888 implants, with follow-up ranging from 12 to 60 months. Two articles addressed CAD/CAM crowns, six discussed abutments, and ten covered implant-supported CAD/CAM frameworks. The mean survival rates were 98.85% for CAD/CAM crowns, 100% for CAD/CAM abutments, and 95.98% for CAD/CAM frameworks. The precision fit of CAD/CAM frameworks surpassed that of 1-piece cast and laser-welded frameworks.^{14,15}

Implant placement using CBCT allows for precise selection and positioning, with the flexibility to adjust implant parameters to fit the clinical situation. Guide fabrication allows customization of fit, offset, material thickness, and manufacturing methods. Finally, an STL file is exported for milling or 3D printing the surgical guide template.^{15,16,17}

Although implant framework misfit alters the biomechanical situation, negative biomechanical sequelae could not be confirmed from the included studies. Biologically, bone resorption cannot develop as a result of framework misfit. From a mechanical perspective, the framework stresses and screw stresses and instability increase with misfit, but the clinical significance of this remains unclear.¹⁸

3D PRINTING IN IMPLANTOLOGY

Additive Manufacturing (AM) or 3D printing has revolutionized dental implantology by enhancing various aspects of implant procedures. It enables the creation of precise drill guides, copings, and frameworks for implants and restorations. 3D printing is also widely used for manufacturing metal frameworks for removable partial dentures (RPDs), fixed partial dentures (FPDs), and splinting implant impression abutments, offering increased accuracy, customization, and efficiency in the production of dental components.^{19,20}

Production of Drill Guides in Dental Implants

Drill guides play a critical role in ensuring the precise placement of dental implants by providing accurate specifications for insertion position, angles, and depth. This precision helps bridge the gap between the planned and actual procedures, optimizing both aesthetic outcomes and the stability of surrounding tissues. Incorrect placement can lead to reduced success rates

and compromised prosthesis reliability. Therefore, the accuracy of 3D-printed surgical guides is crucial in enhancing the success and longevity of dental implants.²¹

Custom Implant Trays

3D printing facilitates the production of highly accurate and customizable implant trays. With CAD software and advanced 3D printers, nearly all aspects of custom tray manufacturing are streamlined. This enhances workflow efficiency, particularly for implant-supported dentures in edentulous patients, and offers higher clinician satisfaction compared to traditional custom trays. Therefore, the ease and customization of 3D printing are driving its increasing adoption in clinical settings.²¹

Creating the Surgical Guides

3D-printed surgical guides improve precision, minimize operational errors, and enhance treatment predictability. These guides fall into two categories:

1. **Dynamic Surgical Guides:** Real-time mechanical or optical systems that display the procedure on a screen.
2. **Static Surgical Guides:** Lab-manufactured guides using SLA technology, created by perforating jaw models.

Traditional guides rely on panoramic radiographs, which can introduce errors like distortion and unclear details. In contrast, modern guides integrate CBCT, intraoral scanning, and CAD to achieve high accuracy. After finalizing the treatment plan, surgical guides are fabricated using SLA technology, ensuring reliable outcomes.²¹ 3D printing enhances the production of accurate and customizable implant trays, streamlining the manufacturing process with CAD software and advanced 3D printers. This improves workflow efficiency, particularly for implant-supported dentures in edentulous patients, leading to higher clinician satisfaction. The growing ease and customization offered by 3D printing are driving its widespread adoption in clinical settings.

When creating surgical guides, 3D-printed options—both dynamic (real-time systems) and static (lab-manufactured using SLA technology)—offer enhanced precision and reduced operational errors. Unlike traditional guides, which rely on panoramic radiographs that may introduce distortion, modern guides use CBCT, intraoral scanning, and CAD for high accuracy. These guides ensure reliable outcomes when fabricated with SLA technology after finalizing the treatment plan.

A study using the R2GATE program demonstrated that CBCT-based digital surgical guides significantly improve precision and are expected to see widespread adoption in clinical practice.²²

3D printing for dental implants utilizes a variety of materials to enhance precision and efficiency. Metal materials, such as titanium meshes and implants, are produced using techniques like Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Polymer materials, including surgical guides and implant models, are crafted with Stereolithography (SLA), Digital Light Processing (DLP), and PolyJet methods. Resin materials, often used for surgical guides and models, are created using VPP technology, though further research is needed for optimization. Data from intraoral optical scanners and CBCT scans is converted into STL files, refined in 3D modeling software, and printed layer-by-layer using SLA, DLP, or MultiJet (MJ) techniques. After printing, post-processing ensures the products are defect-free and durable. While SLA remains the most widely used method, DLP and MJ are gaining popularity due to their advanced capabilities.^{23,24,25,26}

Future Directions

Research is needed to optimize titanium mesh parameters, including thickness, pore diameter, and shape, to ensure mechanical strength. Clinical trials must assess the long-term outcomes

and complications of AM-manufactured implants. Hybrid approaches combining 3D printing with milling may also be necessary for achieving specific application objectives.²⁷

A review was conducted to assess the current evidence on the use of 3D printing technology in dental implantology, focusing on three main areas: customized dental implants, the manufacturing workflow for surgical implant guides, and factors related to implant-supported prostheses, including metal frameworks, secondary ceramic or polymer superstructures, and 3D implant analog models. The review concluded that while clinical evidence on additively manufactured titanium and zirconium implants is limited, these materials show promise in terms of survival rates and mechanical properties. 3D printing has proven to be highly effective for manufacturing surgical implant guides, with MultiJet printers providing the highest accuracy. Additionally, the quality of 3D-printed prosthetic structures, particularly those made from metallic alloys, is significantly improving. However, to meet specific application requirements, combining 3D printing with other technologies, such as milling, may still be necessary.²⁸

Role Of Artificial Intelligence In Implant

AI applications in implant dentistry have introduced a range of innovations, enhancing digital tools and advanced instruments for treatment planning and prognosis assessment. These technologies streamline workflows, reduce human error, and improve the accuracy of clinical diagnoses. AI plays a crucial role in data analysis and decision-making, with key applications including data digitization, bone quality evaluation, tissue segmentation, implant fixture determination, and analysis for implant planning and prognosis. By automating these processes, AI helps clinicians make more informed decisions, ensuring better patient outcomes and more efficient treatment planning.²⁹

AI has evolved over years to mimic the way the human brain functions, applying computational techniques to understand intelligent behavior and develop tools that replicate it. In dental implantology, digital planning software is increasingly used by practitioners to create virtual surgical guides, ensuring precise implant placement during surgery. AI enhances this process by analyzing CBCT images to assess bone quality and quantity, allowing clinicians to detect bone loss accurately. Through AI-driven 3D modeling, the precise size, shape, and angle for implant placement are determined, providing optimal guidance for successful implant surgeries.³⁰

AI offers numerous advantages in implant dentistry, with machine learning being a key component. The primary goal of machine learning is to allow machines to learn from data and make independent decisions. By analyzing large datasets, machine learning assists in evidence-based decision-making and helps create personalized treatment plans tailored to the patient's needs. These algorithms enable precise identification of bone quality and quantity, ensuring accurate implant placement and reducing failure rates. As a result, surgery time is minimized, aesthetics are improved, and patient comfort is enhanced. AI algorithms, including convolutional neural networks (CNN), analyze radiographs for implant classification and complications, significantly improving diagnostic precision. These deep learning models provide insights into bone health from panoramic radiographs, correlating with CBCT measurements, and supporting better implant stability and osseointegration.^{31, 32}

Despite many advantages, in the field of AI, there are ethical concerns and problems. The first issue to address is the maintenance of balance between the knowledge and the skill of dentists along with the use of technology. Practitioners should not be dependent on predictive models but instead, be confident in their professional knowledge and judgment. Some of the other ethical issues are the protection of patient privacy, safeguarding data, and unfair biases. It is essential to resolve these problems by setting regulations to manage the technology.³³

The integration of AI into implant dentistry has revolutionized the field, bringing remarkable advancements in accuracy and precision. By leveraging AI, personalized treatment plans can be developed, long-term success can be predicted, and potential complications can be detected before they arise. These innovations lead to better decision-making and more efficient treatment, ensuring successful outcomes for implant placements. As AI continues to evolve, it will further shape the future of implant dentistry, enhancing diagnostic capabilities, improving treatment planning, and ultimately leading to safer procedures, reduced risks, and better patient outcomes.

Enhanced Diagnostics with AI and ML

Artificial intelligence (AI) and machine learning (ML) are significantly enhancing diagnostics and treatment planning in implant dentistry, especially for clinicians with limited experience in identifying implants. AI-based recognition software has proven effective in identifying implant types with an accuracy ranging from 93.8% to 98%. Additionally, AI models that predict implant success by integrating patient-specific risk factors are showing promise, with osseointegration prediction accuracy varying between 62.4% and 80.5%. Ongoing advancements indicate that optimizing implant design parameters like porosity, length, and diameter can reduce stress at the implant-bone interface by 36.6%, improving implant success. Combining 3D imaging with CBCT data will further enhance implant recognition accuracy, and innovative deep learning methods, such as 1-shot and less-than-1-shot learning, hold the potential to improve models with smaller datasets. Open and standardized datasets are crucial for accelerating AI-driven advancements in implantology, helping to refine predictive analytics and optimize treatment outcomes.³⁴

Digital Workflow and Automation

AI-enhanced digital data acquisition tools, such as facial scanners, intraoral scanners (IOS), and cone-beam computed tomography (CBCT), play a critical role in ensuring precise data collection and integration, minimizing manual segmentation, and improving surgical accuracy. These technologies allow for advanced implant planning by identifying edentulous areas and evaluating bone dimensions, while AI algorithms further enhance decision-making by predicting potential complications and improving treatment outcomes. AI models demonstrate high accuracy in identifying and classifying dental implant fixtures from radiographic images, which streamlines the treatment workflow. With the integration of these advanced technologies, digital workflows and automation are set to transform the efficiency and precision of reconstructive implant dentistry.³⁵

Customized Implant Solutions

3D printing technology has revolutionized dental implantology by enabling the production of patient-specific implants and prosthetics, significantly enhancing both functional and aesthetic outcomes. This versatile manufacturing solution, utilizing a range of materials like polymers, ceramics, metals, and composites, has improved production speed, precision, and reliability, while reducing waste and reliance on manual labor. The integration of scanning, visualization, and CAD with 3D printing has led to advancements in dental implant fixtures and restorations, such as temporary crowns and bridges. A variety of dental products, including surgical guides, implant fixtures, abutments, and prosthetic superstructures, can now be fabricated using 3D printing. Advanced resin materials processed through technologies like SLA (Stereolithography) and DLP (Digital Light Processing), along with high-quality polymers like PEEK and metal alloys printed through FFF (Fused Filament Fabrication) and PBF (Powder Bed Fusion), are transforming the landscape of dental prosthetics. These innovations have reduced turnaround times, allowing for the rapid production of prostheses with minimal adjustments. One remarkable application is the root analog dental implant, fabricated immediately after tooth extraction using 3D printing to replicate the natural anatomy of the tooth root for a precise fit. Hybrid implants combining titanium root forms with zirconia crowns

further enhance bioactivity and osseointegration, reducing the risk of peri-implantitis and tissue loss. This hybrid approach, along with advancements in bioactive materials, promises to set new standards in precision, efficiency, and patient care, ultimately transforming dental restoration and rehabilitation workflows.^{35, 36}

Guided Implant Surgery

Advancements in computer-aided design and manufacturing (CAD/CAM) technology for guided implant surgery have significantly enhanced the accuracy and predictability of dental implantology. By integrating surgical planning with prosthetic designs, clinicians can place implants with precision, ensuring that the implants align with the patient's prosthetic needs. This integration also allows for the provision of immediate temporary restorations at the time of implant placement, improving patient satisfaction. Prosthetically directed implant placement optimizes implant positioning, minimizing surgical complications such as nerve damage, sinus perforation, and bone dehiscence. Using computer-guided implant placement and drill guides, clinicians can achieve precise and predictable outcomes, marking a significant advancement in improving overall success rates in dental implantology.³⁴

Augmented and Virtual Reality in Training

The integration of Virtual Reality (VR) in implant dentistry has revolutionized education and clinical applications by offering a 3D immersive environment. Initially a teaching tool, VR now enhances preoperative planning and implant placement, reducing errors. For clinicians, it provides precise positioning through computer-guided stents and simulations, while also improving patient communication with visual treatment plans. VR simulations offer students a realistic, patient-free practice environment for skill refinement. Clinically, VR is applied across implantation stages, streamlining planning and execution for better outcomes. With advanced 3D simulation capabilities, VR surpasses traditional imaging, offering more accurate virtual models of dentition, enhancing patient safety and procedural precision.³⁵

VR modeling can provide a detailed examination by enabling surgeons to manipulate images through translation, rotation, and scaling, allowing for identification of deformities or conditions that may be overlooked with traditional 2 D imaging.³⁶

VR serves as a valuable tool for surgical training and education in dental implants. Unlike traditional classroom teaching, it offers a practical learning experience. By enabling students and surgeons to repeatedly practice surgical skills in a risk-free environment, VR bridges the gap between theoretical knowledge and clinical proficiency.³⁷ The integration of VR in dental curriculums has not only enhanced learning efficiency but also reduced educational costs and faculty workload by offering a platform for skill acquisition and objective assessment. VR has transformed dental training by shifting from passive observation to active skill development, ensuring patient safety is uncompromised.³⁸

VR-guided preoperative surgical planning, combined with high-resolution CT scans, enables the creation of detailed 3D jawbone models. These models segment anatomical structures to facilitate precise implant positioning. The planning process optimizes factors such as bone density and implant angulation, ensuring the best placement strategy. Additionally, this technology allows for the creation of 3D-printed surgical guides with pre-drilled holes, guaranteeing accurate and efficient implant placement during surgery. This integration of VR and advanced imaging enhances surgical precision, reduces complications, and improves overall treatment outcomes.³⁹

Intraoperatively, the surgical guide is securely positioned on the patient's jaw, directing the surgeon to drill precise osteotomy holes and place implants according to the preoperative virtual plan. VR technology also supports the assessment and management of soft tissues, ensuring comprehensive planning. Intraoperative imaging enhances surgical precision, while Cone-beam computed tomography (CBCT) evaluates implant placement accuracy and identifies any anatomical variations. The fusion of preoperative and intraoperative data in real-

time allows continuous adjustments to the surgical plan, ensuring the procedure aligns with the desired outcomes. Augmented reality (AR) further enhances precision by overlaying virtual information, such as planned implant positions, onto the live surgical view. The integration of VR, CBCT, and AR in guided surgery ensures highly accurate implant placement while minimizing complications and optimizing treatment success.⁴⁰

Integrating VR into implant dentistry requires advancements in tracking technologies and combining it with AI and AR. AI analyzes patient data, simulates implant scenarios, predicts complications, and tailors strategies for individual cases. AR enhances VR by overlaying virtual implant plans onto the live surgical field, improving precision. VR systems for personalized training can transform dental education, especially with affordable, mobile-compatible solutions for remote learning. Early VR and AR integration into curricula fosters skill development, while balancing VR simulations with hands-on methods ensures well-rounded competence.⁴¹

Biocompatible and Smart Materials

Achieving biocompatibility in dental Implants to ensure that the implant material not only performs its intended function but also integrates with the biological milieu is paramount for the success of its integration with the bone and surrounding tissues.⁴²

Biocompatible implant materials play a crucial role in osseointegration by minimizing inflammation and immune reactions, promoting peri-implant tissue health, and improving implant longevity. Factors like surface roughness, topography, ion release, implant design, and surgical techniques all influence the biological response. Coatings and bioactive substances are being explored to enhance tissue integration and reduce inflammation. Personalized immunomodulation strategies are gaining interest, as immune responses vary among individuals. Ongoing research focuses on standardizing surface characterization, conducting long-term evaluations, and addressing material wear and stability to improve the performance and reliability of implant materials.^{43,44,45}

Although biocompatibility has advanced, challenges remain, including improving surface modifications, developing new materials, and tailoring treatments to individual patient needs. Ongoing research focuses on novel materials and surface modifications to optimize immunomodulatory responses and improve long-term outcomes.^{46,47,48}

Teledentistry and Remote Monitoring

In the future, implantology will greatly benefit from advancements in teledentistry and wearable sensors. These technologies will enable remote monitoring of patients, providing real-time feedback on implant healing and integration. Wearable sensors will track factors like bone growth, implant stability, and tissue health, offering clinicians valuable data without the need for in-person visits. Additionally, language model programs, powered by AI, will be capable of efficiently collecting and analyzing patient data, such as healing progress and functionality of implants, to provide more accurate assessments and optimize treatment plans. These innovations will enhance patient care, improve outcomes, and reduce the need for frequent clinic visits.⁴⁹

Conclusion and summary

Digital technologies are reshaping implant dentistry, driving improvements in treatment precision, patient outcomes, and overall efficiency. Key innovations such as intraoral scanners, CAD/CAM, and CBCT are enhancing diagnostic accuracy and optimizing implant placement. The integration of 3D printing is accelerating prosthesis production and streamlining clinical workflows. Moreover, the future holds significant potential for robotics and artificial intelligence to further enhance surgical accuracy and boost implant success rates. Looking ahead, continuous advancements in digital implantology promise to further revolutionize patient care, with innovations paving the way for even greater clinical outcomes and efficiency in the years to come.

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