REVIEW ARTICLE

International Journal of Dental Materials (ISSN: 2582-2209 (Online))
DOI: http://dx.doi.org/10.37983/IJDM.2026.8104

Embracing Digital Technology in Implantology: From Current Practice to Future Potential

Islam Abdelaziz Mohamed Eweis[1], Rana Rakha[2], Sonali Badve[3], Archana Nimale[4], Rohan Chokshi[5], Monica Milagros Parra Rodil[6,7], Sandeep Singh[8,*]

[1] Banisuef University, Banisuef, Egypt.
[2] Faculty of Dental Medicine, Al-Azhar University, Cairo, Egypt.
[3] Bharti Vidyapeeth Dental College, Pune, Maharashtra, India.
[4] Government Dental College, Aurangabad, Maharashtra, India.
[5] A.M.C. Dental College, Ahmedabad, Gujarat, India.
[6] Universidad Iberoamericana AV. Francia 129, Santo Domingo, Dominican Republic.
[7] Florida International University, Miami, FL, United States.
[8] Postgraduate Institute of Dental Sciences, Rohtak, Haryana, India.

Corresponding author:
Sandeep Singh
Postgraduate Institute of Dental Sciences, Rohtak, Haryana, India.
Email: drsandeepsingh011@gmail.com

Article History
Received: 27th October 2025
Accepted: 8th January 2026
Published: 28th March 2026

Abstract

Digitalization has transformed the field of implantology, enabling clinicians to achieve higher precision, efficiency, and predictability across all phases of treatment. This review explores the key digital technologies currently applied in implant dentistry, including cone-beam computed tomography, intraoral scanners, computer-aided design/computer-aided manufacturing systems, static and dynamic guided surgery, and emerging applications of artificial intelligence. These innovations have optimized diagnosis, virtual treatment planning, and surgical execution, enabled minimally invasive procedures and enhanced patient outcomes. Additionally, digital workflows have streamlined prosthetic design and fabrication, reduced chairside time and improved communication between clinicians, laboratories, and patients. However, challenges such as high initial investment, steep learning curves, software interoperability issues, and data security concerns remain barriers to universal adoption. Future research should focus on integrating artificial intelligence with robotics, advancing 3D printing for fully customized implants, and developing cost-effective, open-source solutions to make digital implantology more accessible worldwide. By critically reviewing current evidence, this paper highlights how digitalization continues to shape the future of implant dentistry and emphasizes the need for ongoing training, research, and innovation.

Keywords: Digital implantology, CBCT, Guided surgery, CAD/CAM, Intraoral scanner, AI in dentistry.

Cite this article as: Eweis IAM, Rakha R, Badve S, Nimale A, Chokshi R, Rodil MMP, Singh S. Embracing Digital Technology in Implantology: From Current Practice to Future Potential. **Int J Dent Mater. 2026;8(1):16-25.**

1. Introduction

Digitalization in dentistry refers to the transformation of traditional, analogue procedures into streamlined digital workflows to enhance diagnostic accuracy, treatment planning, and clinical outcomes. In implantology, digitalization integrates a range of technologies including cone-beam computed tomography (CBCT), intraoral scanners, CAD/CAM systems, 3D printing, computer-guided surgery, and artificial intelligence (AI) based planning tools [1,2]. Together, these technologies have redefined the way clinicians plan and execute implant treatment, resulting in greater accuracy, fewer complications, and improved patient experience.

Several key factors have driven the rapid adoption of digital technology. Studies report that over half of dental clinics worldwide now use 3D radiography, and among those, most plan implants digitally, reflecting a clear shift toward technology-driven care [3]. Rising patient expectations for minimally invasive, faster, and more predictable treatments have further fuelled this change. Digital workflows enable more precise visualisation of anatomical structures, improved communication between clinicians and laboratories, and more predictable restorative outcomes, aligning well with patient-centred care models [4].

Traditionally, implant dentistry relied on two-dimensional radiographs, stone models, and freehand surgical placement, which were prone to errors related to operator skill and material distortion. These analogue methods often led to inaccuracies in implant positioning, longer treatment times, and patient discomfort. The advent of CBCT imaging, digital impressions, and CAD/CAM technology has transformed these processes, offering three-dimensional visualisation, virtual treatment planning, and fabrication of surgical guides and patient-specific restorations that enhance both surgical precision and prosthetic fit [5,6].

This review aims to provide a comprehensive summary of current digital technologies used in implantology, critically evaluate their advantages and limitations, and discuss their clinical applications in diagnosis, surgery, and prosthetic phases. Additionally, it highlights the challenges associated with widespread adoption, such as cost, training requirements, and software interoperability and explores future directions, including AI-assisted planning, robotic placement systems, and cost-effective integrated digital workflows that may further enhance accessibility and treatment predictability (Figure 1).

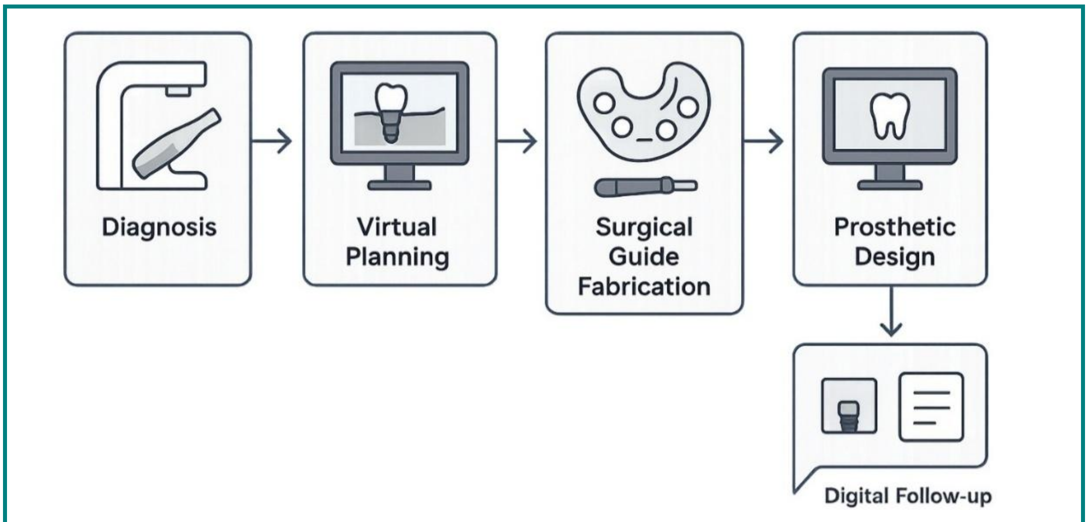

Figure 1. Digital Workflow in Implantology.

2. Digital Technologies in Implantology

2.1 Clinical sources

Digital imaging represents one of the foundational pillars of modern implantology. It includes three-dimensional (3D) imaging [CBCT], software for virtual treatment planning, and accurate assessment of bone volume and quality. This subsection explores how these components offer advantages over older methods, their limitations, and their accuracy in practice.

2.1.1 CBCT for 3D imaging, advantages over 2D radiography

CBCT allows visualisation of dento-alveolar and maxillofacial anatomy in three dimensions, significantly improving diagnostic precision. Where conventional 2D radiographs (intraoral periapical, panoramic) suffer from superimposition, distortion (foreshortening, elongation), and an inability to show bucco-lingual dimensions reliably, CBCT overcomes many of these drawbacks. For example, CBCT provides a clearer view of vital anatomical structures, including the inferior alveolar nerve, mental foramina, incisive canal, and bone concavities, which are often ambiguously or incompletely represented in 2D images [7].

In implant planning, CBCT has become nearly indispensable, especially when the width of the alveolar ridge must be assessed, or in posterior jaws where vertical height and bucco-lingual width are critical. Studies show that while panoramic radiography and intraoral periapical radiographs are useful in simpler cases, they often misrepresent critical dimensions [8, 9]. Thus, CBCT is used to reduce the risk of complications by enabling more accurate surgical planning [9].

2.1.2 Software for Virtual Treatment Planning

Beyond imaging, software tools enable virtual treatment planning. After CBCT acquisition (often merged with digital surface scans), virtual prosthetic designs can be used to drive implant position relative to prosthetic emergence, functional occlusion, and aesthetics. Tools like Romexis 3D Implantology, 3Shape Implant Studio, and others enable interactive manipulation of implant position, depth, angulation, and virtual restoration design.

Clinical studies comparing virtual planning vs actual implant placement show some deviations [10]. In a multicentre study involving edentulous patients, implants placed using mucosal-supported templates showed mean horizontal deviations [neck/apex] and angular deviations around 5°, depending on jaw region and support type. While the errors exist, the procedure is generally considered predictable when software planning and guide design are done properly (Figure 2) [10]. Virtual implant planning offers several significant advantages over traditional freehand assessment. Digital planning software allows clinicians to accurately determine the ideal implant length, diameter, and angulation based on three-dimensional evaluation of the available bone. Multiplanar CBCT visualization enables identification of potential complications, including cortical perforation, proximity to anatomical structures (inferior alveolar nerve, sinus floor, nasal cavity), and inadequate buccolingual bone thickness. The software also assists in evaluating the need for bone augmentation, ridge expansion, sinus lifting, or simultaneous grafting before placement. By integrating prosthetic design with anatomical constraints, virtual planning supports prosthetically-driven implant positioning, enhances surgical predictability, and minimizes the risk of intra-operative complications [9,10].

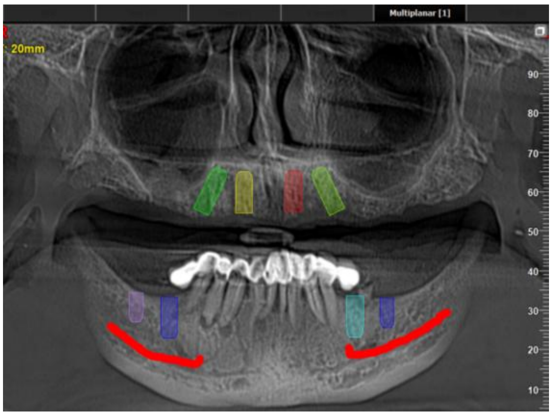

Figure 2. Virtual treatment planning.

2.1.3 Accuracy in Bone Volume and Quality Assessment

Assessing bone volume (quantity) and structure (quality, e.g., cortical vs. trabecular) is critical for deciding implant size, shape, and surgical approach. Multi-slice CT (MSCT) is a medical CT system that acquires multiple slices simultaneously using multiple detector rows, producing high-resolution images with accurate Hounsfield Unit (HU) values. It is considered a clinical gold standard for assessing bone density, cortical thickness, and 3D anatomy. Micro-CT is a research-level imaging modality that provides extremely high-resolution (micron-level) 3D images, enabling detailed evaluation of trabecular and cortical bone microarchitecture. It is not used in patients but serves as the gold standard for in vitro assessment of bone quality.

When high-resolution and properly calibrated, CBCT can approach the gold-standard modalities such as MSCT or micro-CT in certain measurements. For example, a study [11] scanning edentulous human mandibles with multiple CBCT devices vs. MSCT and micro-CT found that parameters like trabecular thickness, cortical thickness, and bone volume fraction could be quantified reliably in many, though not all, CBCT devices; however, some devices overestimated bone quantity or misrepresented fine trabecular architecture [11]. Manual radiographs often show burnout, where overexposed areas lose detail, especially around thin cortical bone, making defect detection less reliable. Digital imaging reduces this problem through better exposure control, wider dynamic range, and post-processing tools. As a result, digital radiographs provide clearer bone margins, more accurate measurements, and improved diagnostic precision compared with manual films.

However, there are limitations. Absolute density measurements from CBCT (grayscale values) are less reliable than Hounsfield Units from medical CT or micro-CT, due to scatter, beam hardening, and nonuniformity. Studies show a weak correlation between CBCT-derived values and true bone mineral density, meaning that while CBCT is valuable for qualitative and relative assessments (thick vs thin bone, cortical vs trabecular), its use for precise quantitative density measurements remains under refinement [12].

2.2 Intraoral scanners and digital impressions

Digital impressions (using intraoral scanners, IOS) are a key component of modern implant workflows. They replace conventional impression materials (elastomers, PVS, etc.) by scanning intraoral surfaces and implant scan-bodies, producing digital files (STL or similar) for prosthetic design and manufacturing.

Multiple *in vitro* studies and systematic reviews report that IOS can achieve accuracy (trueness and precision) comparable to conventional impression techniques in many scenarios [13-15]. For partial edentulous cases or single-implant restorations, IOS often yield lower deviations, especially when scanning smaller spans [13]. For example, one study showed that the TRIOS3 and CS3600 IOS had better mean trueness and precision versus some conventional closed-tray or open-tray elastomeric impression methods for two neighbouring implants [14]. Patients also report greater comfort (no impression tray, less gag reflex, no mixing of materials), and clinics often gain time savings (no impression material handling, fast digital transfers). Although some of these are anecdotal, reviews note consistent time and workflow advantages [15].

2.2.1 Comparison to conventional impressions

While IOS performs well, there are contexts in which conventional impressions still outperform digital ones. In full-arch, edentulous or long-span implant restorations, conventional impression techniques have exhibited lower distortion in some studies. For example, in complete-arch cases, the accuracy (trueness) of conventional impressions is still superior or at least more consistent than IOS in many reports [16]. Also, the accuracy of digital impressions tends to deteriorate as inter-implant distance increases or the scanning span becomes larger.

The choice of scanner manufacturer, scanning strategy, and whether the scan body library is reliable also matter. At the same time, conventional impressions have their own limitations, including the risk of dimensional changes in impression materials, the need for splinting impression copings to reduce movement, and the frequent requirement of custom trays to control material thickness and ensure proper support. These factors introduce additional steps and technique sensitivity, which can affect reproducibility and clinical efficiency.

2.2.2 Limitations

2.2.2.1 Learning curve: Effective use of IOS requires technique sensitivity: keeping scan bodies clean, managing soft-tissue retraction, avoiding distortions, scanning strategy matters [e.g. stitching errors]. Operators with less experience may introduce more errors.

2.2.2.2 Cost: Upfront cost of the scanner hardware, software, maintenance, training time, and possibly needing labs or infrastructure that support digital workflows.

2.2.2.3 Span and edentulous cases: Larger span scanning, full arch, implant scan bodies in edentulous situations are more challenging for digital methods. As noted, precision/trueness falls off in some full arch studies [17]. This drop in accuracy occurs because intraoral scanners rely on stitching multiple images together. As the scanning path becomes longer, small alignment errors accumulate, leading to greater deviation over large distances. The absence of anatomical landmarks in edentulous arches further reduces the scanner's ability to maintain spatial orientation.

2.3 CAD/CAM Technology

CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) underpins a lot of prosthetic and surgical guide fabrication in implantology. It applies from designing surgical guides to custom abutments and final prostheses, using a variety of materials. Surgical guides in implantology are used to transfer the virtual implant plan accurately to the patient's mouth, ensuring correct angulation, position, and depth during drilling. They improve precision, reduce surgical errors, and help in flapless or minimally invasive procedures. Common types include pilot-drill guides (guide only the initial drill), partial/limited guides (guide several steps of drilling), and fully guided systems (control all drilling steps and sometimes implant placement). Guides can be tooth-supported, mucosa-supported, or bone-supported, depending on the clinical condition and extent of edentulism.

2.3.1 Designing surgical guides

CAD/CAM is used to convert virtual implant planning into physical surgical guides. Guides are designed in software [with planned implant positions from CBCT and prosthetic setup] and then manufactured (via 3D printing or milling). Several studies [18,19] have compared different guide designs, support types [tooth, mucosa, bone-supported], and manufacturing methods. Guide accuracy is influenced by guide fit, support type, stability during use, manufacturing precision, and the properties of the metal sleeves/drills used [18,19].

2.3.2 Custom abutments and prosthesis fabrication

While an analogue workflow only permits designing gingival crown contours to suit the patient, a digital workflow, via digital scanning and designing customised abutments and implants, allows for a better emergence profile and increased success rates. A recent randomised controlled trial found that in immediate implant placement in Class II extraction sockets, customised CAD/CAM titanium abutments had significantly better soft tissue [shallower probing depths], esthetics, and less crestal bone loss than stock abutments at 12 months. Another study over 3-years comparing titanium, titanium nitride, and zirconia CAD/CAM abutments observed that zirconia abutments had more failures (especially in posterior areas). In contrast, titanium/titanium nitride abutments had superior survival [20].

2.3.3 Materials used

CAD/CAM systems use a wide range of materials depending on the indication. 3D printing commonly employs resins, nylon (PA12), photopolymers, and titanium or cobalt–chromium alloys through metal laser sintering for surgical guides and frameworks. For milling, pre-sintered ceramics (e.g., zirconia, alumina) are milled in a softer, chalk-like state, allowing faster machining with less bur wear, followed by high-temperature sintering to achieve final strength. Fully sintered ceramics (used in wet milling) require more rigid machines and diamond burs because of their high density and hardness.

Milling units have evolved from 3-axis systems (3D milling) to 4D/5D milling, which allows additional tilt and rotation of the block or spindle. This improves access, accuracy, and the ability to mill complex undercuts and anatomic contours. Drill bits/burs vary in grit, geometry, and material (typically carbide or diamond-coated) to accommodate different materials and maintain precision.

Titanium remains the gold standard for strength, biocompatibility, and mechanical stability. Zirconia is favoured for esthetics, especially in anterior regions. Still, it may be at higher risk of fracture under high-load conditions (posterior) and may entail more technical complications in certain designs [20].

Polyether ether ketone (PEEK) is increasingly used (in crowns, abutments, prosthetic substructures) due to favourable weight, resilience, and shock absorption. Studies testing different combinations (abutment + crown material) show that hybrid combinations (e.g. PEEK or zirconia abutment or crown) have distinct force absorption behaviours, and fracture strength can vary with material pairings and after aging [21]. Also, other ceramics (e.g. lithium disilicate) and composite or hybrid materials are used in conjunction with CAD/CAM for crowns or abutment-crowns.

2.4 Guided implant surgery

Guided implant surgery refers to using guides or navigation systems instead of freehand placement to improve accuracy and predictability. There are static surgical guides, fully guided or partially guided, and dynamic navigation systems (real-time tracking).

2.4.1 Static vs. dynamic navigation

Static guides: Pre-planned implant positions are transferred via a physical guide (drill guide)- cannot adjust mid-surgery.

Dynamic navigation includes real-time optical or electromagnetic tracking of drills and sometimes the patient, allowing adjustments during surgery based on intraoperative findings. Advantages include flexibility, the ability to handle cases with limited space, and sometimes reduced need for guide support.

2.4.2 Clinical accuracy and time efficiency

Studies indicate that both static and dynamic guided surgery significantly improve positional accuracy over freehand placement. For example, a prospective clinical study found mean deviations (platform, apical, angular) were much lower for dynamic navigation and static guides vs freehand [23]. In dynamic navigation, entry (coronal) deviations and apical deviations are often in the 0.8-1.1 mm range, angular deviations around 3-4°, whereas freehand errors are significantly larger [24].

Static guides reduce surgical time (drilling sequence more predictable, minimal adjustment), though guide fabrication can add preoperative time. Dynamic navigation may involve longer setup, calibration, and intraoperative tracking steps. But some studies suggest that over time and with experience, dynamic navigation can become more efficient [23].

2.4.3 Evidence on success rates

Guided surgery (static or dynamic) shows high implant survival rates. Many studies report survival rates >95% at 1–2-year follow-ups. [23-25] Complication rates tend to be lower for guided placements, especially regarding mis-angulation, critical structure injury, and prosthetic misfit. For example, the systematic review and meta-analysis comparing implant placement accuracy (robotic, static guide, dynamic navigation vs freehand) found that guided modalities have significantly less deviation and better predictability [25].

2.5 Artificial Intelligence (AI) and Machine Learning (ML)

AI/ML are newer entrants into implantology, promising to augment or partly automate tasks such as image analysis, planning, and prediction of outcomes.

2.5.1 Automated image analysis (bone density, nerve tracing)

AI models have been developed to assist in the segmentation of radiographic images (CBCT, panoramic, etc.), automatically identifying structures like nerves, sinus floor, and bone boundaries. This speeds up planning, reduces inter-observer variability, and can improve safety by avoiding vital structures. While many of these systems are still in development or *in silico*/*in vitro*, the early results are promising [26].

2.5.2 Predictive treatment planning

Some studies use AI to predict implant success or risk (e.g. failure, marginal bone loss, peri-implantitis) based on preoperative imaging and patient factors. A systematic review found AI algorithms reaching accuracy rates as high as ~99.8% in some contexts, though the sensitivity/specificity vary widely (67-95% sensitivity, 78-100% specificity) [27]. One randomised controlled trial using CBCT-based AI assistance reported higher implant success (92% vs 78%) and fewer complications in the AI-assisted group vs traditional evaluation [28].

2.5.3 AI in outcome prediction

Beyond planning, AI is being applied to predicting long-term outcomes- risk of peri-implantitis, bone loss, prosthetic complications, and survival rates. These models may combine imaging, patient medical history, bone quality, implant geometry, and loading protocols.

The variability in performance is high; methodological differences (datasets, follow-up, definitions of success/failure) make comparison difficult. More standardised datasets and prospective clinical validation are needed [29].

3. Clinical Applications

Digitalization in implantology is not just about tools; it fundamentally alters how patients are diagnosed, restored, and monitored. This section examines concrete clinical applications in each phase.

3.1 Diagnosis and treatment planning

Digital imaging (CBCT, intraoral scans), virtual wax-ups, and digital set-ups are now central to treatment planning. Virtual prosthetic set-ups allow clinicians to visualize the final tooth design, emergence profile, occlusion, and spatial relationships before surgery, ensuring that implant placement is prosthetically driven rather than just anatomically constrained. The integration of CBCT data and intraoral scans permits accurate assessments of bone volume, nerve position, the spatial relations of adjacent teeth, and esthetic zones. For example, Flügge et al. compared various implant planning software and found that tools for prosthetic set-ups, virtual articulators, and 3D reconstructions vary across systems. Planning software that includes virtual wax-ups or prosthetic set-ups yields more predictable outcomes in prosthetic aesthetics and function [30]. Digital workflows contribute to higher patient satisfaction by enabling better visualization and communication of expected outcomes, while also allowing the clinician to incorporate the patient's aesthetic expectations directly into the final prosthetic design.[31].

3.2 Surgical phase

Digital technologies have markedly improved accuracy during implant placement. Guided surgery (static guides), dynamic navigation, and robot-assisted systems generally produce smaller deviations (platform, apex, and angular) from planned positions compared to freehand placement. A prospective study comparing dynamic navigation, static guides, and freehand found mean global platform and apical deviations of approximately 1 mm for guided techniques, versus significantly larger deviations in the freehand group [31]. Minimally invasive approaches, such as flapless or punch techniques enabled by guided surgery, help reduce surgical trauma, postoperative pain, swelling and post-surgical bone loss. For example, in augmented sites treated with dynamic navigation and flapless approach, patients had favourable outcomes and uneventful healing [32].

3.3 Prosthetic phase

In the prosthetic phase, digital workflows facilitate customized restorations and careful occlusion planning. Virtual wax-ups, prosthetic set-ups, and virtual articulators available in many implant planning software allow simulation of occlusion, emergence profile, and tooth morphology before final prosthetic fabrication. Such planning improves esthetics and reduces the risk of complications from poor occlusion or prosthesis misfit [30].

CAD/CAM fabrication (milling or 3D printing) of abutments, crowns, and prostheses using the digital impressions ensures better fit, reduced adjustments/remakes, and more efficient lab-clinical communication. Digital occlusion analysis tools can evaluate contacts and adjustments virtually, decreasing adjustment time in the clinic. Systems like T-Scan use ultra-thin pressure-sensitive sensors to record dynamic occlusal contacts, timing, and force distribution with high precision, offering a more objective assessment than traditional articulating paper. This leads to fewer post-delivery adjustments and improved patient satisfaction [30].

3.4 Postoperative follow-up

After implant placement and prosthetic restoration, digital tools enable better follow-up and monitoring. CBCT and intraoral scans can be used to monitor marginal bone levels over time, assess soft tissue changes, and detect early signs of complications (e.g. bone loss, peri-implantitis). Serial digital images allow comparisons, and superimposition of scans can quantify changes in bone volume and soft tissue contours.

Implant stability and osseointegration may also be monitored digitally (e.g. via resonance frequency analysis devices whose data can be integrated into digital patient records), and sometimes using intraoral scanners or optical scanning for prosthetic interfaces to check for fit over time. Digital workflows also improve documentation and allow more accurate tracking of outcomes. While long-term studies are still evolving, early evidence suggests that these digital monitoring tools help in timely intervention and may improve long-term implant success [33].

4. Advantages and limitations of digital workflow in implantology

The integration of digital workflow in implantology offers several notable advantages, including enhanced precision and predictability through prosthetically driven planning, reduced chairside time, and improved patient experience. Additionally, digital systems promote better communication among clinicians, laboratories, and patients while facilitating efficient data storage and retrieval for long-term follow-up. However, these benefits are counterbalanced by limitations such as high initial costs, a steep learning curve, dependence on technology, and potential data security concerns (Table 1).

Table 1. Advantages and limitations of digital workflow in implantology

Advantages	Limitations
Precision and predictability: Prosthetically driven planning and guided surgery reduce angular and linear deviations compared to freehand placement [34].	**High cost**: Investment in scanners, CBCT, CAD/CAM, and software can be prohibitive for smaller practices [35].
Reduced chairside time: Digital impressions and CAD/CAM restorations minimize appointment duration and adjustments [36].	**Learning curve**: Requires training and experience to avoid operator errors and maximize accuracy [37].
Enhanced communication: Seamless data sharing between dentist, lab, and patient improves workflow and case acceptance [38].	**Dependence on technology:** Calibration errors, hardware/software failures, and incompatibilities may compromise outcomes [39].
Improved patient experience: Less invasive impressions, reduced gag reflex, and higher comfort lead to better patient satisfaction [40].	**Data security and inter-operability issues:** Risk of privacy breaches and lack of standardized file formats [41].
Data storage and retrieval: Digital records can be archived, retrieved, and compared over time, aiding long-term follow-up [42].	

5. Future directions

The landscape of implantology is evolving rapidly, and several emerging trends promise to further transform how implants are planned, placed, restored, and managed.

5.1 Integration of AI with robotics for fully automated implant placement

Robotic systems integrated with AI are expected to advance toward more autonomous or semi-autonomous implant placement. Research shows how AI algorithms can assist with diagnosis, planning, and surgical execution, paired with robotic arms or systems to improve precision and reduce human error [43]. Such systems may allow for real-time feedback, automatic adjustments during surgery, and reduced manually-driven errors in angulation, depth, or position. However, ethical, regulatory, and safety issues need thorough addressing [43].

5.2 Virtual reality [VR] and augmented reality [AR] for training and real-time surgery guidance

VR refers to a fully immersive, computer-generated environment that allows users to interact with simulated clinical scenarios, whereas AR overlays digital information, such as anatomical landmarks or planned implant positions, onto the real-world surgical field in real time. VR and AR are gaining traction for both education and intraoperative guidance. A narrative review showed that AR overlays (e.g. real-time display of anatomical landmarks) improve surgical precision, while VR provides immersive surgical training that improves skill retention and reduces errors in early learners [44]. An *in vitro* study demonstrated that mixed reality-based navigation for implant placement greatly improves accuracy in terms of platform, mid, and apex point deviation and angular deviation when compared to traditional freehand teaching methods [45].

AR-guided freehand surgery using head-mounted displays to project virtual planning onto patient anatomy has also been explored, suggesting potential for improved guidance in live surgery [46].

5.3 Development of cost-effective, open-source software

To make digital workflows more accessible, particularly in resource-limited settings, there is growing interest in cost-effective and open-source software solutions. The primary advantage of these platforms lies in their ability to reduce financial barriers, as high licensing fees, recurring subscription costs, and reliance on proprietary ecosystems often limit the adoption of digital implantology technologies in smaller clinics, academic institutions, and developing regions. While specific publications are less numerous in this area compared to imaging or robotics, broader movements in digital health emphasize lowering barriers to entry by developing affordable platforms. The need is clear: high license costs, proprietary software, and limited access constrain adoption. This creates an opportunity for open-source solutions or shared platforms [47].

5.4 Personalized implants with 3D printing and bioprinting

The trend toward personalization is strong; using 3D printing to create patient-specific surgical guides, custom abutments, and prostheses is already well established. The next level is bioprinting, which may allow incorporation of biologically active materials, scaffolds for tissue regeneration, or even printed bone or soft tissue structures in conjunction with implants.

Although direct clinical examples of bio-printed implants are limited currently, preclinical studies and material science advances suggest that biocompatible scaffolds, composite biomaterials, and 3D printed custom implants are becoming more feasible. These advances may improve osseointegration, esthetics, and functional adaptation [48].

5.5 Use of blockchain for secure dental records

Blockchain is a decentralized, distributed digital ledger technology in which data are stored in a chain of time-stamped blocks that are cryptographically linked and shared across multiple nodes. Each transaction or record is validated through a consensus mechanism, making the stored information tamper-resistant, transparent, and verifiable without reliance on a central authority. These fundamental characteristics make blockchain particularly suitable for secure healthcare and dental data management.

Blockchain technology presents significant potential for enhancing the security, transparency, and integrity of dental patient data management. Current literature highlights its prospective applications in safeguarding patient privacy, facilitating secure data sharing, improving supply chain traceability, and strengthening trust in the accuracy and authenticity of medical and dental records [49].

For example, immutable ledger systems can ensure that once records are stored, they cannot be altered without a trace, which is important for medico-legal accountability. Federated learning models for AI can use blockchain for traceable, auditable updates of training data and models [50]. Another research thesis explored proof-of-concept systems for using blockchain in dentistry for permission-based sharing of patient records, showing feasibility in distributed but secure record-keeping.

6. Conclusion

Digitalization has transformed implantology by streamlining workflows, improving diagnostic accuracy, and enabling highly precise implant placement. Technologies such as CBCT, intraoral scanners, CAD/CAM, and guided surgery have collectively enhanced treatment predictability and patient satisfaction. Digital workflows also promote improved communication between clinicians, laboratories, and patients, resulting in better collaboration and more customized treatment outcomes. Despite these advancements, challenges remain, particularly related to the high cost of equipment, steep learning curves, and concerns regarding data security and interoperability. The evidence supporting digital implantology is growing, but further well-designed clinical trials and costeffectiveness studies are needed to validate long-term outcomes and justify widespread adoption. Ultimately, the future of implantology will rely on continuous innovation, integration of AI and robotics, and the development of accessible technologies. Clinicians must commit to ongoing education and skill development to stay updated with evolving digital tools and to maximize the benefits for their patients.

Conflicts of interest: The Authors declared no conflicts of interest.

Financial support: None

References

1. Joda T, Waltimo T, Probst-Hensch N, Pauli-Magnus C, Zitzmann NU. Health data in dentistry: an attempt to master the digital challenge. Public Health Genomics. 2019 Sep 19;22(1-2):1-7. https://doi.org/10.1159/000501643
2. D'haese J, Ackhurst J, Wismeijer D, De Bruyn H, Tahmaseb A. Current state of the art of computer-guided implant surgery. Periodontol 2000. 2017;73(1):121-133. https://doi.org/10.1111/prd.12175
3. Thondati Poornachandra Rao, Manandhar S, Pinnamaneni M, Kalakota S, Bhola R, Singh S. Digital implant planning and guided surgery: current trends and clinical outcomes. Sch J Dent Sci. 2025;12(4):43-48.
4. Bernauer SA, Zitzmann NU, Joda T. The complete digital workflow in fixed prosthodontics updated: a systematic review. Healthcare (Basel). 2023;11(5):679. https://doi.org/10.3390/healthcare11050679
5. Vercruyssen M, Cox C, Naert I, Jacobs R, Teughels W, Quirynen M. Accuracy and patient-centered outcome variables in guided implant surgery: a RCT comparing immediate with delayed loading. Clin Oral Implants Res. 2016;27(4):427-432. https://doi.org/10.1111/clr.12583
6. Mangano FG, Veronesi G, Hauschild U, Mijiritsky E, Mangano C. Trueness and precision of four intraoral scanners in oral implantology: a comparative in vitro study. PLoS One. 2016;11(9):e0163107. https://doi.org/10.1371/journal.pone.0163107
7. Benavides E, Rios HF, Ganz SD, An CH, Resnik R, Reardon GT, Feldman SJ, Mah JK, Hatcher D, Kim MJ, Sohn DS. Use of cone beam computed tomography in implant dentistry: the International Congress of Oral Implantologists consensus report. Implant Dent. 2012;21(2):78-86. https://doi.org/10.1097/ID.0b013e31824885b5
8. Ramis-Alario A, Tarazona-Alvarez B, Cervera-Ballester J, Soto-Peñaloza D, Peñarrocha-Diago M, Peñarrocha-Oltra D, Peñarrocha-Diago M. Comparison of diagnostic accuracy between periapical and panoramic radiographs and cone beam computed tomography in measuring the periapical area of teeth scheduled for periapical surgery. A cross-sectional study. J Clin Exp Dent. 2019;11(8):e732-e738. https://doi.org/10.4317/jced.55986
9. Deeb G, Antonos L, Tack S, Carrico C, Laskin D, Deeb JG. Is cone-beam computed tomography always necessary for dental implant placement?. Journal of Oral and Maxillofacial Surgery. 2017;75(2):285-9. https://doi.org/10.1016/j.joms.2016.09.029
10. Vinci R, Manacorda M, Abundo R, Lucchina AG, Scarano A, Crocetta C, et al. Accuracy of edentulous computer-aided implant surgery as compared to virtual planning: a retrospective multicenter study. J Clin Med. 2020;9(3):774. https://doi.org/10.3390/jcm9030774
11. Van Dessel J, Nicolielo LF, Huang Y, Slagmolen P, Politis C, Lambrichts I, Jacobs R. Quantification of bone quality using different cone beam computed tomography devices: accuracy assessment for edentulous human mandibles. Eur J Oral Implantol. 2016;9(4):411-424.
12. Cassetta M, Stefanelli LV, Di Carlo S, Pompa G, Barbato E. The accuracy of CBCT in measuring jaws bone density. Eur Rev Med Pharmacol Sci. 2012;16(10):1425-1429.
13. Albanchez-González MI, Brinkmann JC, Peláez-Rico J, López-Suárez C, Rodríguez-Alonso V, Suárez-García MJ. Accuracy of digital dental implants impression taking with intraoral scanners compared with conventional impression techniques: a systematic review of in vitro studies. Int J Environ Res Public Health. 2022;19(4):2026. https://doi.org/10.3390/ijerph19042026
14. Roig E, Garza LC, Álvarez-Maldonado N, Maia P, Costa S, Roig M, et al. In vitro comparison of the accuracy of four intraoral scanners and three conventional impression methods for two neighboring implants. PLoS One. 2020;15(2):e0228266. https://doi.org/10.1371/journal.pone.0228266
15. Afrashtehfar KI, Alnakeb NA, Assery MKM. Accuracy of intraoral scanners versus traditional impressions: a rapid umbrella review. J Evid Based Dent Pract. 2022;22(3):101719. https://doi.org/10.1016/j.jebdp.2022.101719
16. Ma B, Yue X, Sun Y, et al. Accuracy of photogrammetry, intraoral scanning, and conventional impression techniques for complete-arch implant rehabilitation: an in vitro comparative study. BMC Oral Health. 2021;21:636. https://doi.org/10.1186/s12903-021-02005-0
17. Pozzi A, Arcuri L, Carosi P, Laureti A, Londono J, Wang HL. Photogrammetry versus intraoral scanning in complete-arch digital implant impression: a systematic review and meta-analysis. Clin Implant Dent Relat Res. 2025;27(3):e70059. https://doi.org/10.1111/cid.70059
18. Berta GM, Luigi C, Miguel PD, Carlos BJ. Prospective clinical study on the accuracy of static computer-assisted implant surgery in patients with distal free-end implants. Conventional versus CAD-CAM surgical guides. Clin Oral Implants Res. 2025;36(3):314-324. https://doi.org/10.1111/clr.14384
19. Kasradze D, Kubilius R. Influence of guide support on the accuracy of static Computer-Assisted Implant Surgery (sCAIS) in partially edentulous cases using a keyless guiding system: an in vitro study. BMC Oral Health. 2025;25(1):563. https://doi.org/10.1186/s12903-025-05955-x
20. Robaian A, Hamed MM, Ahmed Y, Hassanein FEA. Comparative evaluation of customized CAD/CAM vs. stock titanium abutments for immediate implant placement in class II extraction sockets: a randomized controlled trial. Dent J (Basel). 2025;13(8):371. https://doi.org/10.3390/dj13080371
21. Ferrari M, Tricarico MG, Cagidiaco MC, Vichi A, Gherlone EF, Zarone F, Sorrentino R. 3-year randomized controlled prospective clinical trial on different CAD-CAM implant abutments. Clin Implant Dent Relat Res. 2016;18(6):1134-1141. https://doi.org/10.1111/cid.12418
22. Elsayed A, Farrag G, Chaar MS, Abdelnabi N, Kern M. Influence of different CAD/CAM crown materials on the fracture of custom-made titanium and zirconia implant abutments after artificial aging. Int J Prosthodont. 2019;32(1):91-96. https://doi.org/10.11607/ijp.6137
23. Younis H, Lv C, Xu B, Zhou H, Du L, Liao L, Zhao N, Long W, Elayah SA, Chang X, He L. Accuracy of dynamic navigation compared to static surgical guides and the freehand approach in implant placement: a prospective clinical study. Head Face Med. 2024;20(1):30. https://doi.org/10.1186/s13005-024-00433-1
24. Pellegrino G, Ferri A, Del Fabbro M, Prati C, Gandolfi MG, Marchetti C. Dynamic Navigation in Implant Dentistry: A Systematic Review and Meta-analysis. Int J Oral Maxillofac Implants. 2021;36(5):e121-e140.

https://doi.org/10.11607/jomi.8770

25. Wu XY, Huang ZL, Liu BL, Lv XL, Shi JY, Lai HC. Accuracy of Implant Placement with Robotic Surgery, Dynamic Navigation, Fully Static Guide, and Freehand Surgery: A Systematic Review and Network Meta-analysis. Int J Oral Maxillofac Implants. 2025;0(0):1-28. https://doi.org/10.11607/jomi.11531
26. Jindanil T, Marinho-Vieira LE, de-Azevedo-Vaz SL, Jacobs R. A unique artificial intelligence-based tool for automated CBCT segmentation of mandibular incisive canal. Dentomaxillofac Radiol. 2023;52(8):20230321. https://doi.org/10.1259/dmfr.20230321
27. Alqutaibi AY, Algabri RS, Alamri AS, Alhazmi LS, Almadani SM, Alturkistani AM, Almutairi AG. Advancements of artificial intelligence algorithms in predicting dental implant prognosis from radiographic images: A systematic review. J Prosthet Dent. 2025;134(6):2177-2188. https://doi.org/10.1016/j.prosdent.2024.10.036
28. Rajan RSS, Kumar HSK, Sekhar A, Nadakkavukaran D, Feroz SMA, Gangadharappa P. Evaluating the Role of AI in Predicting the Success of Dental Implants Based on Preoperative CBCT Images: A Randomized Controlled Trial. J Pharm Bioallied Sci. 2024;16(Suppl 1):S886-S888. https://doi.org/10.4103/jpbs.jpbs_1117_23
29. Elbanna L, Rahimi H, Mohammadi M, Saeedi N, Ahmadyar R, Rezaee N, Nikferjam AZ, Safi P, Singh S. Integration of digital technologies in implant dentistry: Workflow, challenges, and opportunities. Eur J Dent Oral Health. 2026;7(1):22–28. https://doi.org/10.24018/ejdent.2026.7.1.13414.
30. Flügge T, Kramer J, Nelson K, Nahles S, Kernen F. Digital implantology—a review of virtual planning software for guided implant surgery. Part II: Prosthetic set-up and virtual implant planning. BMC Oral Health. 2022;22(1):23. https://doi.org/10.1186/s12903-022-02057-w
31. Kafedzhieva A, Vlahova A, Chuchulska B. Digital technologies in implantology: A narrative review. Bioengineering. 2025;12(9):927. https://doi.org/10.3390/bioengineering12090927.
32. Wachol K, Morawiec T, Nowak-Wachol A, Kubaszek B, Kasprzyk-Kucewicz T, Baldi D, Machorowska-Pieniążek A, Skucha-Nowak M, Cholewka A. Comparative analysis of implant prosthesis treatment planning and execution following bone repair procedures using dynamic surgical navigation in augmented areas. Coatings. 2022;12(8):1099. https://doi.org/10.3390/coatings12081099.
33. Saini RS, Bavabeedu SS, Quadri SA, Gurumurthy V, Kanji MA, Kuruniyan MS, Binduhayyim RI, Avetisyan A, Heboyan A. Impact of 3D imaging techniques and virtual patients on the accuracy of planning and surgical placement of dental implants: A systematic review. Digital Health. 2024;10:1-9. https://doi.org/10.1177/20552076241253550
34. Tahmaseb A, Wismeijer D, Coucke W, Derksen W. Computer technology applications in surgical implant dentistry: a systematic review. Int J Oral Maxillofac Implants. 2014;29 Suppl:25-42. https://doi.org/10.11607/jomi.2014suppl.g1.2
35. Bessadet M, Drancourt N, El Osta N. Time efficiency and cost analysis between digital and conventional workflows for the fabrication of fixed dental prostheses: A systematic review. J Prosthet Dent. 2025;133(1):71-84. https://doi.org/10.1016/j.prosdent.2024.01.003
36. Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. J Prosthet Dent. 2013;109(2):121-8. https://doi.org/10.1016/S0022-3913(13)60028-1
37. Revilla-León M, Att W, Özcan M, Rubenstein J. Comparison of conventional, photogrammetry, and intraoral scanning accuracy of complete-arch implant impression procedures evaluated with a coordinate measuring machine. J Prosthet Dent. 2021;125(3):470-8.
38. Joda T, Zarone F, Ferrari M. The complete digital workflow in fixed prosthodontics: a systematic review. BMC Oral Health. 2017;17(1):124. https://doi.org/10.1186/s12903-017-0415-0
39. Wang J, Wang B, Liu YY, Luo YL, Wu YY, Xiang L, Yang XM, Qu YL, Tian TR, Man Y. Recent Advances in Digital Technology in Implant Dentistry. J Dent Res. 2024;103(8):787-799. https://doi.org/10.1177/00220345241253794
40. Afrashtehfar KI, Alnakeb NA, Assery MK. Accuracy of intraoral scanners versus traditional impressions: A rapid umbrella review. Journal of Evidence-Based Dental Practice. 2022;22(3):101719. https://doi.org/10.1016/j.jebdp.2022.101719
41. Schierz O, Hirsch C, Krey KF, Ganss C, Kämmerer PW, Schlenz MA. Digital dentistry and its impact on oral health-related quality of life. J Evid Based Dent Pract. 2024;24(1S):101946. https://doi.org/10.1016/j.jebdp.2023.101946
42. Mangano F. Digital dentistry. J Dent. 2021;109:103693. https://doi.org/10.1016/j.jdent.2021.103693
43. Saeed A, Alkhurays M, AlMutlaqah M, AlAzbah M, Alajlan SA. Future of using robotic and artificial intelligence in implant dentistry. Cureus. 2023;15(8):e43209. https://doi.org/10.7759/cureus.43209
44. Lin PY, Chen TC, Lin CJ, Huang CC, Tsai YH, Tsai YL, Wang CY. The use of augmented reality (AR) and virtual reality (VR) in dental surgery education and practice: A narrative review. J Dent Sci. 2024;19(Suppl 2):S91-S101. https://doi.org/10.1016/j.jds.2024.10.011
45. Wang X, Guan M, Liu L, Xu R, Yang Z, Liu Z, Li D, Tang C, Wen N, Li H. The impact of mixed reality training method on novice trainees of dental implants: an in vitro study. BMC Oral Health. 2025;25(1):1379. https://doi.org/10.1186/s12903-025-06366-8.
46. Bochet Q, Raoul G, Lauwers L, Nicot R. Augmented reality in implantology: Virtual surgical checklist and augmented implant placement. J Stomatol Oral Maxillofac Surg. 2024;125(12 Suppl 2):101813. https://doi.org/10.1016/j.jormas.2024
47. Reen GS, Mohandas M, Venkatesan S. Decentralized patient centric e-health record management system using blockchain and IPFS. In: *2019 IEEE Conference on Information and Communication Technology (CICT)*, Allahabad, India, 2019. p. 1–7. https://doi.org/10.1109/CICT48419.2019.9066212
48. Vickram AS, Infant SS, Manikandan S, Sowndharya BB, Gulothungan G, Chopra H. 3D bio-printed scaffolds and smart implants: evaluating functional performance in animal surgery models. Ann Med Surg (Lond). 2025;87(6):3618-3634. https://doi.org/10.1097/MS9.0000000000003333
49. Mokhamed T, Talib MA, Moufti MA, Abbas S, Khan F. The potential of blockchain technology in dental healthcare: a literature review. Sensors. 2023;23(6):3277. https://doi.org/10.3390/s23063277
50. Mardini DC, Sharma M, Madathil S. Blockchain for Trustworthy Artificial Intelligence in Dentistry. JDR Clin Trans Res. 2025;10(4):469-471. https://doi.org/10.1177/23800844241303483.