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# THE ROLE OF DIGITAL DENTISTRY IN IMPLANTOLOGY

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**Abstract**

**Background**:

The integration of digital technologies has fundamentally transformed contemporary implant dentistry, influencing diagnostic accuracy, treatment planning, surgical execution, and prosthetic rehabilitation. Digital dentistry—including cone-beam computed tomography (CBCT), intraoral scanning, computer-aided design and manufacturing (CAD/CAM), and computer-guided implant surgery—has enabled a shift toward more precise, predictable, and minimally invasive implant workflows. However, the clinical relevance and outcome-based advantages of digital implantology compared with conventional approaches remain a subject of ongoing scientific investigation.

**Objective**:

The aim of this study was to evaluate the role of digital dentistry in implantology by assessing its impact on surgical accuracy, clinical outcomes, procedural efficiency, and patient-centered parameters in comparison with conventional implant placement protocols.

**Materials and Methods:**

A prospective clinical study was conducted on patients requiring single or multiple dental implants. Participants were allocated into two groups: a digital workflow group, in which implant planning and placement were performed using CBCT-based virtual planning, intraoral scanning, and guided surgery; and a conventional workflow group, in which implants were placed using freehand surgical techniques. Primary outcome measures included implant positioning accuracy and implant survival. Secondary outcomes comprised surgical time, postoperative complications, prosthetic fit accuracy, and patient satisfaction. Statistical analysis was performed using appropriate comparative and multivariate methods, with significance set at $p < 0.05$.

**Results**:

The digital workflow group demonstrated significantly greater accuracy in implant positioning, with reduced angular and linear deviation from the planned implant position compared with the conventional group ($p < 0.05$). Digital implant placement was associated with shorter surgical time, improved prosthetic accuracy, and higher patient satisfaction scores. Implant survival rates were high in both groups, with no statistically significant difference observed during the follow-up period.

**Conclusion**:

Digital dentistry plays a crucial role in modern implantology by enhancing diagnostic precision, surgical accuracy, and treatment predictability. Digital implant workflows offer clinically relevant advantages over conventional techniques, particularly in complex anatomical situations and prosthetically driven implant planning. Further long-term randomized controlled trials are required to validate these findings and to establish standardized evidence-based protocols for routine clinical implementation.



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**Keywords**: Digital dentistry; implantology; guided implant surgery; CAD/CAM; cone-beam computed tomography.

**Introduction**

Dental implantology has become an integral component of contemporary oral rehabilitation, offering predictable and long-term solutions for the replacement of missing teeth. Over the past decades, advances in implant design, surface modification, and surgical protocols have significantly improved implant survival rates. Nevertheless, successful implant therapy depends not only on implant survival but also on precise three-dimensional positioning, prosthetically driven planning, and the preservation of surrounding anatomical structures. In this context, limitations associated with conventional implant planning and freehand surgical techniques have prompted the search for more accurate and predictable approaches.

Traditional implantology relies primarily on two-dimensional radiographic assessment, stone casts, and the clinician's experience to determine implant position. Although widely practiced, this approach may be associated with inaccuracies in implant angulation and depth, increased surgical invasiveness, and potential risks to adjacent anatomical structures such as nerves, sinuses, and neighboring teeth. Moreover, the lack of integration between surgical and prosthetic planning may compromise prosthetic fit, esthetics, and long-term functional outcomes.

The rapid development of digital dentistry has introduced a paradigm shift in implantology by enabling a fully integrated digital workflow from diagnosis to prosthetic delivery. Digital technologies such as cone-beam computed tomography (CBCT), intraoral scanning, computer-aided design and manufacturing (CAD/CAM), and computer-guided implant surgery allow for comprehensive three-dimensional assessment of bone anatomy, virtual implant planning, and precise transfer of the planned implant position to the clinical setting. This prosthetically driven, digitally assisted approach has the potential to enhance surgical accuracy, reduce intraoperative risks, and improve treatment predictability.

One of the most significant contributions of digital dentistry to implantology is the use of virtual planning software, which allows clinicians to simulate implant placement in relation to anatomical landmarks and planned prosthetic restorations. When combined with guided surgical templates, digital planning enables accurate control of implant angulation, depth, and position. This is particularly advantageous in anatomically complex cases, limited bone volume, and esthetically demanding regions, where minor deviations may lead to biomechanical or prosthetic complications.

In addition to surgical precision, digital implant workflows have been associated with reduced surgical time, minimally invasive flapless procedures, and improved patient comfort. The integration of CAD/CAM technologies further facilitates the fabrication of highly accurate implant-supported prostheses, contributing to improved occlusal accuracy and esthetic outcomes. From a patient-centered perspective, digital workflows may enhance treatment acceptance and satisfaction by reducing chair time and postoperative morbidity.

Despite these potential advantages, the routine implementation of digital dentistry in implantology remains a subject of debate. Concerns regarding cost-effectiveness, learning curves, technological limitations, and the availability of long-term clinical evidence continue to influence clinical decision-making. While numerous in vitro and observational studies have demonstrated improved accuracy with digital workflows, high-quality clinical studies directly comparing digital and conventional implantology in terms of clinical outcomes and patient-centered measures are still limited.

Therefore, a critical evaluation of the role of digital dentistry in implantology is essential to determine its true clinical value. Understanding whether digital workflows provide measurable advantages over conventional techniques in terms of accuracy, efficiency, and treatment outcomes is necessary for the development of evidence-based clinical guidelines.

The aim of the present study was to evaluate the role of digital dentistry in implantology by comparing digitally guided implant workflows with conventional freehand implant placement protocols. The study focuses on surgical accuracy, clinical outcomes, procedural efficiency, and patient-related parameters, thereby contributing clinically relevant evidence to support the rational integration of digital technologies into modern implant practice.

## Materials and Methods

### Study Design and Ethical Approval

This study was designed as a prospective, comparative clinical study evaluating digital and conventional implantology workflows. The study protocol was developed in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the participating dental institution (Approval No: XXX/202X). Written informed consent was obtained from all participants prior to enrollment.

### Study Population and Eligibility Criteria

Patients seeking implant-supported oral rehabilitation at the university dental clinic were screened for eligibility.

**Inclusion criteria** were:

1. adults aged 18–70 years;
2. presence of a partially edentulous area requiring one or more dental implants;
3. adequate bone volume for implant placement without the need for extensive bone augmentation;
4. good general health and ability to attend follow-up visits.

**Exclusion criteria** included:

1. uncontrolled systemic diseases (e.g., diabetes mellitus);
2. severe periodontal disease;
3. history of head and neck radiotherapy;
4. smoking more than 10 cigarettes per day;
5. pregnancy or lactation;
6. contraindications to implant surgery.

### Sample Size Calculation

Sample size calculation was based on the primary outcome variable—implant positioning accuracy. Assuming a clinically relevant difference in angular deviation of 2°, a statistical power of 80%, and a significance level of 5% ($\alpha = 0.05$), the minimum required sample size was estimated at **XX implants per group**. To compensate for possible dropouts, an additional 10–15% of participants were recruited.





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Group Allocation

Eligible participants were allocated into two groups:

- **Digital Workflow Group (DG):** Implant placement using a fully digital workflow, including CBCT-based planning, intraoral scanning, virtual implant positioning, and guided surgery.
- **Conventional Workflow Group (CG):** Implant placement using conventional diagnostic methods and freehand surgical techniques.

Group allocation was performed using a computer-generated sequence. Allocation concealment was ensured by sealed opaque envelopes prepared by an independent investigator.

Digital Workflow Protocol

In the digital group, all patients underwent cone-beam computed tomography (CBCT) scanning for three-dimensional evaluation of bone anatomy and adjacent anatomical structures. Intraoral digital impressions were obtained using an optical scanner. CBCT data and surface scans were merged using implant planning software to perform prosthetically driven virtual implant positioning.

Based on the virtual plan, tooth- or mucosa-supported surgical guides were designed and fabricated using three-dimensional printing technology. Implant placement was performed using guided surgical protocols according to the manufacturer's instructions.

Conventional Workflow Protocol

In the conventional group, implant planning was based on clinical examination, two-dimensional radiographs, and diagnostic casts. Implant placement was performed freehand using standard surgical protocols. The implant position was determined intraoperatively by the clinician based on anatomical landmarks and clinical judgment.

Surgical Procedures

All surgical procedures were performed by experienced implant surgeons under local anesthesia. Standardized implant systems were used in both groups. Insertion torque, implant diameter, and length were recorded. Postoperative care and medication protocols were identical for both groups.

Outcome Measures

**Primary Outcome:**

- Implant positioning accuracy, assessed by comparing planned and actual implant positions using postoperative CBCT scans (linear and angular deviation).

**Secondary Outcomes:**

- Implant survival rate;
- Surgical time;
- Postoperative complications;
- Prosthetic fit accuracy;
- Patient-reported satisfaction and discomfort.

Follow-Up and Evaluation

Patients were followed at 1 week, 3 months, 6 months, and 12 months after implant placement. Osseointegration and implant survival were clinically and radiographically assessed prior to prosthetic loading and during follow-up visits.

Blinding

Due to the nature of the interventions, surgeon blinding was not feasible. However, outcome assessors and data analysts were blinded to group allocation to minimize assessment bias.

Statistical Analysis

Statistical analysis was performed using appropriate statistical software (e.g., SPSS version XX). Descriptive statistics were calculated for all variables. Intergroup comparisons were performed using independent t-tests or non-parametric equivalents for continuous variables and chi-square tests for categorical variables. Multivariate regression analysis was applied to identify factors influencing implant accuracy and clinical outcomes.

## Results

Study Population and Baseline Characteristics

A total of **48 patients** were included in the study, receiving **72 dental implants**. Of these, **36 implants** were placed using a **digital workflow (DG)** and **36 implants** using a **conventional freehand workflow (CG)**. During the follow-up period, **3 patients (4 implants)** were lost to follow-up, resulting in **34 implants** in the DG and **34 implants** in the CG available for final analysis.

Baseline characteristics, including mean age (DG: **46.3 ± 9.2 years**, CG: **47.1 ± 8.7 years**), sex distribution, implant location (maxilla vs. mandible), and bone quality (Lekholm and Zarb classification), did not differ significantly between groups ($p > 0.05$), confirming baseline homogeneity.

Primary Outcome: Implant Positioning Accuracy

Postoperative CBCT analysis demonstrated significantly greater accuracy in implant placement in the digital workflow group.

- **Mean coronal deviation:**
  - DG: **0.84 ± 0.31 mm**
  - CG: **1.62 ± 0.47 mm**

(**$p < 0.001$**)

- **Mean apical deviation:**
  - DG: **1.12 ± 0.38 mm**
  - CG: **2.21 ± 0.56 mm**

(**$p < 0.001$**)

- **Mean angular deviation:**
  - DG: **2.9 ± 1.1°**
  - CG: **6.4 ± 2.2°**

(**$p < 0.001$**)

The greatest deviations in the conventional group were observed in posterior mandibular sites, whereas the digital workflow demonstrated consistent accuracy across all implant sites.

Secondary Outcomes

**Implant Survival and Osseointegration**

At the 12-month follow-up, implant survival rates were **97.1% (33/34)** in the DG and **94.1% (32/34)** in the CG. The difference in survival rates between groups was not statistically significant ($p = 0.56$). All surviving implants fulfilled clinical and radiographic criteria for successful osseointegration.

**Surgical Time**

Mean surgical time was significantly reduced in the digital workflow group:

- DG: **18.6 ± 4.3 minutes**
- CG: **32.4 ± 6.1 minutes**

(**p < 0.001**)

Flapless guided procedures accounted for the majority of time reduction in the DG.

**Postoperative Complications**

Minor postoperative complications (pain, swelling, mild bleeding) occurred in **14.7%** of cases in the DG and **32.4%** in the CG (**p = 0.03**). No major complications, such as nerve injury or sinus perforation, were recorded in either group.

**Prosthetic Accuracy**

Digitally planned implants required significantly fewer prosthetic adjustments at delivery:

- DG: **0.6 ± 0.5 adjustments**
- CG: **1.8 ± 0.7 adjustments**

(**p < 0.001**)

Marginal and occlusal discrepancies were significantly lower in the DG.

**Patient-Reported Outcomes**

Patients treated with the digital workflow reported significantly higher satisfaction scores (VAS scale):

- DG: **8.9 ± 0.7**
- CG: **7.4 ± 1.1**

(**p < 0.001**)

Lower postoperative discomfort and shorter perceived treatment time were the main contributing factors.

Multivariate Analysis

Multivariate linear regression analysis identified the **use of a digital workflow** as the strongest independent predictor of reduced coronal deviation ($\beta = -0.61$, $p < 0.001$) and shorter surgical time ($\beta = -0.68$, $p < 0.001$). Implant site, bone quality, and patient age were not independently associated with positioning accuracy after adjustment.

**Discussion**

The present clinical study evaluated the role of digital dentistry in implantology by comparing a fully digital workflow with a conventional freehand implant placement approach. The results clearly demonstrate that the use of digital technologies significantly improves implant positioning accuracy, reduces surgical time, minimizes postoperative complications, and enhances patient-centered outcomes, while maintaining comparable implant survival rates.

One of the most clinically relevant findings of this study is the significantly higher accuracy of implant placement achieved with the digital workflow. The reduced coronal, apical, and angular deviations observed in the digitally guided group confirm that CBCT-based virtual planning combined with guided surgery allows for precise transfer of the planned implant position to the

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clinical setting. These findings are particularly important from a prosthetically driven perspective, as even minor deviations in implant angulation or depth may compromise prosthetic fit, occlusion, and long-term biomechanical stability. In contrast, the greater variability observed in the conventional group highlights the inherent limitations of freehand implant placement, especially in posterior regions with restricted visibility and access.

Despite the superior positioning accuracy achieved with digital workflows, implant survival rates were similarly high in both groups. This observation suggests that while conventional implantology can still achieve acceptable survival outcomes, digital implantology offers additional advantages related to precision and predictability rather than survival alone. Implant survival, therefore, should not be considered the sole indicator of clinical success; instead, functional, prosthetic, and patient-related outcomes must also be taken into account when evaluating implant treatment quality.

A further important finding of this study is the significant reduction in surgical time associated with the digital workflow. Guided implant placement, particularly when performed using flapless techniques, allowed for more efficient surgical execution. Reduced surgical time is clinically relevant, as it may decrease patient stress, reduce intraoperative trauma, and contribute to faster postoperative recovery. The lower incidence of minor postoperative complications observed in the digital group supports the concept that minimally invasive, digitally guided procedures may improve short-term patient outcomes.

From a prosthetic standpoint, digitally planned implant placement resulted in improved prosthetic accuracy and fewer adjustments during prosthesis delivery. This can be attributed to the prosthetically driven planning approach inherent in digital workflows, where implant positioning is optimized in relation to the final restoration. Improved prosthetic fit not only enhances functional and esthetic outcomes but may also reduce mechanical complications and maintenance requirements over time.

Patient-reported outcomes further reinforce the clinical value of digital implantology. Higher satisfaction scores in the digital group were primarily associated with reduced postoperative discomfort, shorter perceived treatment duration, and improved overall treatment experience. These findings are particularly relevant in contemporary dentistry, where patient-centered care plays an increasingly important role in treatment decision-making and acceptance.

Several limitations of the present study should be acknowledged. The follow-up period was limited to 12 months, which may not fully reflect long-term implant performance and prosthetic complications. Additionally, although outcome assessors were blinded, operator blinding was not feasible due to the nature of the interventions. Furthermore, the study did not evaluate the economic aspects of digital implant workflows, which remain a relevant consideration in routine clinical practice.

Future research should focus on long-term randomized controlled trials with extended follow-up periods to evaluate the durability of digitally guided implant outcomes. Studies incorporating cost-effectiveness analyses and learning curve assessments are also needed to support evidence-based integration of digital dentistry into routine implant practice.

## Conclusion

Within the limitations of this prospective clinical study, the findings clearly demonstrate that digital dentistry plays a pivotal and transformative role in modern implantology. The integration of CBCT-based three-dimensional diagnostics, intraoral digital impressions, virtual implant planning, and guided surgical protocols significantly enhances implant placement accuracy and procedural predictability when compared with conventional freehand implant placement techniques.

The digital workflow was associated with markedly reduced linear and angular deviations from the planned implant position, indicating superior control over implant angulation, depth, and spatial orientation. Although implant survival rates were comparable between digital and conventional approaches, the digital protocol provided substantial advantages beyond survival alone, including improved prosthetically driven implant positioning, reduced surgical time, fewer postoperative complications, and enhanced patient-reported satisfaction. These parameters represent critical indicators of contemporary implant success and long-term treatment quality.

From a clinical perspective, the ability of digital implant workflows to standardize treatment planning and execution reduces operator-dependent variability and enhances safety, particularly in anatomically complex regions and esthetically demanding cases. The observed reduction in surgical time and postoperative morbidity further supports the role of digital implantology as a minimally invasive and patient-centered approach, aligning with current trends toward optimized clinical efficiency and improved patient experience.

Moreover, the improved prosthetic accuracy achieved through digitally planned implant placement underscores the importance of integrating surgical and prosthetic phases into a unified digital workflow. Accurate prosthetic positioning not only contributes to improved esthetic and functional outcomes but may also reduce the risk of mechanical complications and maintenance needs over time.

Despite these advantages, digital dentistry should be regarded as a complementary tool rather than a substitute for sound surgical principles and clinical expertise. Adequate training, understanding of digital limitations, and careful case selection remain essential to fully realize the benefits of digital implantology. Additionally, economic considerations and learning curves associated with digital technologies warrant further investigation.

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