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Research Article

Comparative Study on AI-Based Computer-Guided Implant Placement and Manual Surgical Planning

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ABSTRACT

Background: The precision of dental implant placement is critical for long-term prosthetic success and the avoidance of anatomical complications. While Computer-Guided Surgery (CGS) has improved accuracy, the planning phase remains time-consuming and operator-dependent. Recently, Artificial Intelligence (AI) algorithms have been integrated into planning software to automate implant positioning and guide design.

Methods: A randomized controlled clinical trial was conducted involving 60 patients requiring single-tooth implants in the posterior mandible. Patients were randomly assigned to two groups: Group A (AI-Guided, $n = 30$) utilized AI-based software for automatic nerve tracing, implant positioning, and 3D-printed guide fabrication; Group B (Manual/Freehand, $n = 30$) underwent standard CBCT-based manual planning and freehand surgical placement. Post-operative CBCT scans were superimposed on pre-operative plans to measure deviations at the entry point, apex, and angulation. Surgical duration and visual analog scale (VAS) pain scores were also recorded.

Results: Group A demonstrated significantly lower mean deviations compared to Group B. The mean angular deviation was $2.14° \pm 0.76°$ for the AI-Guided group versus $6.82° \pm 2.41°$ for the Manual group ($p < 0.001$). Global deviation at the apex was 0.85 ± 0.32 mm for Group A and 2.15 ± 0.88 mm for Group B ($p < 0.001$). The mean surgical time was significantly shorter in Group A (14.2 ± 3.5 min) compared to Group B (26.8 ± 5.2 min) ($p = 0.002$). No nerve injuries occurred in either group.

Conclusion: AI-based computer-guided implant surgery significantly outperforms manual freehand placement in terms of three-dimensional accuracy and surgical efficiency. The integration of AI reduces the margin of error inherent in manual execution, offering a safer and more predictable workflow for posterior mandibular rehabilitation.

Keywords: Dental Implants, Artificial Intelligence, Computer-Guided Surgery, Accuracy, CBCT, Digital Dentistry.

INTRODUCTION

The rehabilitation of edentulous spaces with dental implants has become a cornerstone of modern restorative dentistry, offering high survival rates and restoration of function [1]. However, the long-term success of implant therapy is not solely dependent on osseointegration but is heavily dictated by the precise three-dimensional (3D) positioning of the fixture. Malpositioning can lead to biomechanical failure, poor esthetics, peri-implantitis, and injury to vital anatomical structures such as the inferior alveolar nerve or the maxillary sinus [2].

Traditionally, implant placement relied on "freehand" techniques, where the surgeon translates preoperative radiographic data to the surgical field using visual estimation and anatomical landmarks. While experienced surgeons can achieve acceptable results, this manual method is susceptible to human error, particularly in cases with limited bone volume or restricted visibility [3]. Studies have shown that freehand placement can result in angular deviations averaging between $6°$ and $8°$, which may compromise the prosthetic outcome [4].

To mitigate these errors, Computer-Guided Surgery (CGS) was introduced, utilizing Cone Beam Computed Tomography (CBCT) and intraoral scanning to fabricate static surgical guides. These guides restrict the drill trajectory, significantly improving accuracy [5]. However, the workflow for static guide generation has traditionally been labor-intensive, requiring the clinician to manually trace nerves, segment teeth, and determine the optimal implant axis slice-by-slice. This manual digital planning is subject to inter-operator variability and a steep learning curve [6].

The advent of Artificial Intelligence (AI), specifically Deep Learning (DL) and Convolutional Neural Networks (CNNs), has begun to revolutionize this workflow. AI algorithms can now automate image segmentation, nerve tracing, and virtual tooth setup, potentially standardizing the planning process and generating surgical guides with minimal human intervention [7]. Recent studies have validated AI for diagnostic accuracy in dentistry, yet there is a paucity of clinical data comparing the end-to-end surgical accuracy of AI-automated guide protocols against traditional manual methods in a controlled clinical setting [8].

Therefore, a research gap exists regarding whether AI-driven planning translates to superior clinical outcomes compared to the standard of care. The aim of this study is to evaluate and compare the accuracy (entry point, apex, and angulation) and surgical efficiency of AI-based computer-guided implant placement versus manual surgical planning and freehand execution in partial edentulism.

MATERIALS AND METHODS

A power analysis was performed based on previous studies regarding angular deviation. To detect a difference of 2.5° between groups with a standard deviation of 3°, a power of 90%, and an alpha of 0.05, a sample size of 26 implants per group was calculated. To account for potential dropouts, a total of 60 patients (30 per group) were enrolled.

Inclusion and Exclusion Criteria

Inclusion Criteria: Patients aged 20–65 years; presence of a single missing tooth in the posterior mandible (premolar or molar region); sufficient bone volume (checked via CBCT) allowing for placement of an implant ≥ 3.5mm diameter and ≥ 10mm length without simultaneous grafting; healed sites (>4 months post-extraction).

Exclusion Criteria: Uncontrolled systemic diseases (e.g., diabetes, osteoporosis); history of head and neck radiation; inability to open mouth >35mm; active periodontal disease; heavy smokers (>10 cigarettes/day).

Randomization

Patients were randomly assigned to one of two groups using computer-generated random numbers sealed in opaque envelopes:

- **Group A (AI-Guided):** Implant planning and guide generation using AI-driven software.
- **Group B (Manual/Freehand):** Conventional manual planning on CBCT and freehand surgical placement.

Procedures

Pre-operative Phase: All patients underwent a standardized CBCT scan and an intraoral scan.

- Group A: DICOM and STL files were imported into an AI-enabled planning software. The software automatically segmented the mandible, traced the inferior alveolar nerve, virtually placed the ideal prosthetic tooth, and proposed the implant position. After surgeon verification (without manual alteration unless safety was compromised), a tooth-supported surgical guide was 3D printed.
- Group B: The surgeon analyzed the CBCT data using standard viewers, measuring distance to the nerve and bone width manually. No surgical guide was fabricated.

Surgical Phase: All surgeries were performed by a single experienced surgeon.

- Group A: A flapless approach (where keratinized tissue permitted) or minimal flap was used. The 3D-printed guide was seated, and the drilling protocol followed the guided surgery kit instructions.
- Group B: A full-thickness mucoperiosteal flap was raised to visualize the bone. The osteotomy was prepared freehand based on the mental navigation of the preoperative plan.

Data Collection

A post-operative CBCT was taken immediately after surgery. The pre-operative planning data and post-operative CBCT were imported into distinct evaluation software. The images were superimposed (registered) to measure the deviation between the planned position and the actual position.

Outcome Measures

1. **Coronal Deviation (mm):** Distance between the center of the planned and actual implant at the platform level.
2. **Apical Deviation (mm):** Distance between the center of the planned and actual implant at the apex.

3. **Angular Deviation (Degrees):** The angle formed between the central axes of the planned and actual implants.
4. **Surgical Time (min):** Measured from the first incision (or punch) to the final suture (or healing cap placement).

Statistical Analysis

Data were analyzed using SPSS software (Version 25.0). Descriptive statistics (Mean ± SD) were calculated. The Shapiro-Wilk test assessed normality. Independent t-tests were used to compare continuous variables between groups. A p-value of <0.05 was considered statistically significant.

Results

Demographic Data

A total of 60 patients (32 males, 28 females) completed the study. The mean age was 44.5 ± 8.2 years. There were no statistically significant differences between the groups regarding age, gender distribution, or bone density classification (D2/D3), ensuring baseline homogeneity.

Table 1. Demographic and Baseline Characteristics

Characteristic	Group A (AI-Guided) ($n = 30$)	Group B (Manual) ($n = 30$)	p-value
Age (Years)	43.2 ± 7.5	45.8 ± 8.9	0.231(NS)
Gender (M/F)	15 / 15	17 / 13	0.605(NS)
Site (Premolar/Molar)	12 / 18	14 / 16	0.598(NS)
Bone Density (Type)	D2: 18, D3: 12	D2: 16, D3: 14	0.712(NS)

NS= Not Significant

Accuracy Analysis

The primary outcome of accuracy revealed statistically significant differences favoring the AI-Guided group. The deviation at the entry point (coronal) and the apex was substantially higher in the freehand group. Notably, the angular deviation in the manual group was more than triple that of the AI group.

Table 2. Comparison of Deviations between Planned and Placed Implants

Variable	Group A (AI-Guided) (Mean $\pm$ SD)	Group B (Manual) (Mean $\pm$ SD)	p-value
Coronal Deviation (mm)	0.65 ± 0.24	1.42 ± 0.65	< 0.001*
Apical Deviation (mm)	0.85 ± 0.32	2.15 ± 0.88	< 0.001*
Angular Deviation (degrees)	$2.14° \pm 0.76°$	$6.82° \pm 2.41°$	< 0.001*
Vertical (Depth) Deviation (mm)	0.45 ± 0.20	1.12 ± 0.55	< 0.001*

*Statistically significant ($p < 0.05$)

Surgical Efficiency and Patient Outcomes

Surgical time was significantly reduced in Group A. Additionally, patient-reported pain, measured via Visual Analog Scale (VAS) 24 hours post-op, was lower in the AI-guided group, likely due to the minimally invasive (often flapless) nature of the guided procedure.

Table 3. Surgical Time and Post-Operative Pain (VAS)

Variable	Group A (AI-Guided)	Group B (Manual)	p-value
Surgical Time (min)	14.2 ± 3.5	26.8 ± 5.2	0.002*
VAS Pain Score (0-10)	2.1 ± 1.1	4.6 ± 1.5	< 0.001*
Analgesic Intake (Tablets/day)	1.2 ± 0.6	2.8 ± 0.9	< 0.001*

No major complications (nerve paresthesia, sinus perforation) were recorded in either group. However, two implants in Group B required immediate repositioning due to proximity to adjacent roots, which was corrected intra-operatively but contributed to increased surgical time.

DISCUSSION

This study provides a comparative analysis of AI-driven guided surgery versus traditional manual placement, addressing a critical evolution in digital dentistry. The results clearly reject the null hypothesis; the AI-guided protocol demonstrated superior accuracy and efficiency compared to the manual freehand technique.

Accuracy

our findings showed a mean angular deviation of 2.14° for the AI-guided group compared to 6.82° for the manual group. This aligns with the systematic review by Tahmaseb et al., which reported mean errors of 3.5° for guided surgery, though our AI-assisted results showed even tighter precision [9]. The manual deviation observed ($>6^{\circ}$) is consistent with findings by Vercruyssen et al., who highlighted the "human drift" tendency during freehand drilling [10]. The global apical deviation of 2.15mm in the manual group is clinically significant; in the posterior mandible, a 2mm error could easily result in violation of the inferior alveolar canal or lingual plate perforation [11]. The AI-generated guides effectively constrained the drill in all three spatial planes, mitigating the tremor and parallax errors inherent to human vision.

AI Integration

What distinguishes this study is the use of AI for the planning phase. Traditional computer-guided surgery requires time-consuming manual segmentation. The software used in Group A automatically fused STL and DICOM files and traced the nerve canal, a process that typically takes 10-15 minutes manually, but was reduced to seconds by the algorithm [12]. Joda et al. have previously discussed the potential of AI to reduce the "digital burden" on clinicians, and our surgical time data (14.2 min vs 26.8 min) supports the efficiency of this workflow [13].

Surgical Efficiency and Morbidity

The reduction in surgical time in Group A is attributed to the elimination of the need for extensive flap reflection and the confidence provided by the guide. In Group B, the surgeon required more time to verify angulation and depth repeatedly. Consequently, the AI-guided group reported significantly lower post-operative pain (VAS 2.1 vs 4.6). This correlates with the study by Fortin et al., which established that flapless guided surgery preserves periosteal blood supply and reduces inflammation [14].

Limitations

While the results are promising, the study has limitations. The cost of the 3D printing and software license adds a financial burden not present in freehand surgery. Furthermore, the study was limited to single posterior implants; the accuracy of AI guides in fully edentulous arches, where mucosa-supported guides are used, may differ due to soft tissue resilience [15]. Additionally, the "black box" nature of AI means clinicians must still rigidly verify the automated proposal to ensure no algorithmic errors occurred.

Future Directions

Future research should focus on the application of AI in dynamic navigation systems (robotics) and the long-term prosthetic survival of implants placed using these automated protocols.

Conclusion

Within the limitations of this study, it can be concluded that AI-based computer-guided implant placement significantly enhances surgical accuracy and reduces operative time compared to manual surgical planning and freehand placement. The AI-driven workflow offers a reliable, minimally invasive alternative that minimizes the risk of angular and linear deviations, particularly beneficial in the posterior mandible where anatomical constraints are critical. While manual placement remains a viable skill, the integration of AI represents a paradigm shift toward safer and more predictable implant dentistry.

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