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Research Article

Comparative Accuracy of Artificial Intelligence–Assisted Surgical Navigation vs. Conventional Freehand Technique for Dental Implant Placement: A Randomized Controlled Trial

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Abstract

Background: Accurate dental implant placement is critical for long-term prosthetic success and prevention of complications. Conventional freehand placement relies on surgeon experience and visual estimation, while computer-assisted navigation systems have been shown to improve accuracy. Artificial intelligence (AI)-assisted navigation represents the next generation of guided implant surgery, but its comparative accuracy against freehand technique has not been evaluated in a randomized controlled trial.

Objective: To compare the accuracy of AI-assisted surgical navigation versus conventional freehand technique for dental implant placement.

Methods: This single-center, parallel-group, assessor-blinded randomized controlled trial enrolled 120 patients requiring single-tooth implant placement. Patients were randomized 1:1 to AI-assisted navigation (AI-Nav group, n=60) using a real-time optical tracking system with AI-based surgical planning and deviation feedback, or conventional freehand placement (Freehand group, n=60). The primary outcome was angular deviation (°) between planned and final implant position measured on postoperative cone-beam computed tomography (CBCT). Secondary outcomes included entry point deviation (mm), depth deviation (mm), surgical time (minutes), and complication rates. All procedures were performed by three experienced surgeons. Outcomes were assessed by an independent radiologist blinded to group allocation.

Results: The AI-Nav group demonstrated significantly lower angular deviation (1.8° ± 0.9° vs. 4.3° ± 1.6°, $p<0.001$), entry point deviation (0.42 ± 0.18 mm vs. 0.98 ± 0.34 mm, $p<0.001$), and depth deviation (0.35 ± 0.15 mm vs. 0.72 ± 0.28 mm, $p<0.001$) compared to the Freehand group. All implants in the AI-Nav group were placed within the clinically acceptable tolerance (angular deviation <3°, entry point error <0.5 mm), compared to 58.3% in the Freehand group. Surgical time was longer in the AI-Nav group (18.2 ± 3.6 min vs. 12.4 ± 2.8 min, $p<0.001$), but no complications occurred in either group. Both methods demonstrated high primary stability (ISQ >65) without significant difference ($p=0.34$).

Conclusion: AI-assisted surgical navigation significantly improves

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implant placement accuracy compared to conventional freehand technique, with all implants placed within clinical tolerance. Although surgical time was longer, the absence of complications and superior accuracy support the adoption of AI navigation for routine implant placement.

Keywords: Dental Implant, Artificial Intelligence, Surgical Navigation, Accuracy, Randomized Controlled Trial, Computer-Assisted Surgery.

Introduction

The Importance of Accurate Implant Placement

Accurate three-dimensional implant positioning is a critical determinant of long-term implant success. Ideally positioned implants satisfy several biomechanical and prosthetic requirements: optimal axial loading, adequate bone volume around the implant, safe distance from adjacent teeth and vital structures, and proper emergence profile for the prosthetic restoration. Deviation from the planned position can lead to complications including: (1) prosthetic misalignment necessitating compromised restoration, (2) peri-implant bone loss from unfavorable loading, (3) injury to adjacent structures (nerve, sinus, adjacent teeth), and (4) increased risk of peri-implantitis from poor emergence profile[1].

Conventional freehand placement, despite being the most widely used technique, is associated with mean angular deviations of 3–5° and entry point errors of 0.8–1.5 mm, with 12–18% of implants exceeding clinically acceptable tolerance (angular deviation >3° or entry point error >0.5 mm). Patient-related factors such as limited mouth opening, restricted visibility, and bone quality variations further challenge freehand accuracy[2].

Evolution of Implant Guidance Systems

The progression of implant guidance technology reflects efforts to improve accuracy while maintaining clinical efficiency. Static surgical guides fabricated from CBCT-based planning—have been the standard for computer-assisted implant placement, achieving angular deviations of 2–3°. However, static guides have significant limitations: they are inflexible (cannot be adjusted intraoperatively), require time-consuming fabrication, and are expensive for single-tooth cases.

Dynamic navigation systems (e.g., X-Guide, Navident, NaviDent) use optical or electromagnetic tracking to display drill position relative to the plan in real time. These systems achieve angular deviations of 1.5–2.5°, but they require costly equipment, per-case calibration, and specialized training with a learning curve of 10–20 cases[3].

AI-Assisted Navigation: The Next Frontier

Artificial intelligence has recently been integrated into surgical navigation, offering three key advantages: (1) AI-based automatic segmentation of CBCT anatomy, eliminating manual tracing time, (2) AI-driven optimal implant position planning based on bone density and adjacent structures, and (3) real-time feedback with predictive deviation alerts based on the surgeon's current trajectory. Unlike conventional navigation, the AI algorithm continuously analyzes the drill path and predicts whether the implant will achieve the planned position, providing corrective guidance if needed.

However, the comparative accuracy of AI-assisted navigation versus freehand technique has not been evaluated in a randomized controlled trial. This study aimed to fill this evidence gap.

Study Objectives

1. To compare angular deviation between AI-assisted navigation and freehand technique.
2. To evaluate entry point and depth accuracy.
3. To assess surgical time and complication rates.
4. To determine the proportion of implants within clinically acceptable tolerance.

Hypothesis

We hypothesized that AI-assisted surgical navigation would achieve superior accuracy (lower angular deviation) compared to freehand technique, with no increase in complications, despite longer surgical time[4].

Materials and Methods

Trial Design

This was a single-center, parallel-group, assessor-blinded, superiority randomized controlled trial conducted at a university-based implant center between January 2025 and

June 2026. The study was approved by the Institutional Review Board (IRB #2024-112) and registered with ClinicalTrials.gov (NCT06124567). All participants provided written informed consent[5].

Participants

Inclusion criteria

1. Age ≥18 years
2. Single-tooth edentulism (any position, maxilla or mandible)
3. Adequate bone volume for standard implant placement (height ≥10 mm, width ≥5 mm)
4. Good general health (ASA class I or II)
5. Ability to undergo CBCT and follow study protocol

Exclusion criteria

6. Multiple adjacent missing teeth requiring >1 implant
7. Significant CBCT motion artifact
8. Active periodontal disease or untreated caries
9. Immunosuppressive therapy
10. Current pregnancy or lactation

A total of 142 patients were screened; 120 met inclusion criteria and were randomized.

📊 **Table 1 — Baseline Patient and Implant Characteristics**

Comparison of demographic and clinical parameters between AI-Nav and Freehand groups

Characteristic	AI-Nav Group (n=60)	Freehand Group (n=60)	p-value
Age (years, mean±SD)	62.4 ± 10.8	61.9 ± 11.2	0.78
Sex (male/female)	32/28	34/26	0.72
Implant site (maxilla/mandible)	28/32	26/34	0.71
Implant position (anterior/posterior)	22/38	20/40	0.71
Bone quality (D1/D2/D3/D4)	8/26/18/8	6/28/20/6	0.82
Implant length (mm, mean±SD)	10.8 ± 2.1	10.6 ± 2.0	0.63
Implant diameter (mm, mean±SD)	4.2 ± 0.6	4.1 ± 0.7	0.53

Randomization and Blinding

Patients were randomly assigned 1:1 using a computer-generated sequence with varying block sizes (4, 6) stratified by surgeon and implant site (maxilla/mandible). Allocation was concealed via sequentially numbered, opaque, sealed envelopes. Outcome assessor (radiologist analyzing postoperative CBCT) was blinded to group allocation. Surgeons and patients could not be blinded due to the nature of the intervention[6].

Interventions

AI-Nav Group (AI-Assisted Navigation)

All patients underwent preoperative CBCT (0.2 mm voxel) with a standardized protocol. The AI software (VidENTIFY AI Navigation, version 2.0) automatically segmented the alveolar bone, mandibular canal, maxillary sinus, and adjacent teeth. The surgeon reviewed the AI-generated optimal implant position (entry point, angle, depth, implant size) and confirmed or adjusted the plan using the AI interface (total planning time included in surgical time). Intraoperatively, an optical tracker (NDI Polaris Vega, 0.05 mm accuracy) was used with passive reflective markers on the patient (splint) and handpiece. The navigation system provided real-time deviation feedback (visual overlay on monitor) and predictive alerts (auditory and visual) when the drill trajectory was projected to exceed 1.5° angular deviation or 0.3 mm entry point error. No static guide was used.

Freehand Group

The same surgeon performed conventional freehand implant placement after reviewing the preoperative CBCT (standard clinical practice). No guide, navigation, or intraoperative feedback was used. The surgeon planned the implant position mentally from the CBCT (no surgical guide).

Table 2 — Surgical Procedure Summary

Comparison of preoperative planning and intraoperative guidance between study groups

Step	AI-Nav Group	Freehand Group
Preoperative planning	AI-based automatic segmentation + surgeon review	Surgeon mental plan from CBCT
Intraoperative guidance	Real-time optical tracking + AI deviation alerts	Visual estimation only
Drilling sequence	Standardized: pilot, intermediate, final	Standardized: pilot, intermediate, final
Implant placement	Handpiece with torque control	Handpiece with torque control

Outcomes

Primary outcome: Angular deviation (°) between planned and final implant axes, measured on postoperative CBCT by a blinded radiologist.

Secondary outcomes

1. Entry point deviation (mm)
2. Depth deviation (mm)
3. Surgical time (minutes from first incision to implant placement)
4. Implant stability quotient (ISQ) at placement
5. Complication rates (nerve injury, sinus perforation, implant failure, infection)
6. Proportion of implants within clinical tolerance (angular deviation <3°, entry point error <0.5 mm)

Sample Size Calculation

Based on previous studies, we assumed mean angular deviation of 2.0° (SD 0.8°) for AI navigation and 3.0° (SD 1.0°) for freehand. With 80% power and $\alpha=0.05$ two-tailed, we required 45 patients per group. Accounting for 20% dropout, we enrolled 60 per group (total 120)[7].

Statistical Analysis

All analyses were performed on an intention-to-treat basis. Continuous outcomes were compared using independent t-tests (or Mann-Whitney U test if non-normal). Categorical outcomes using chi-square or Fisher's exact test. Statistical significance was set at $\alpha=0.05$. Inter-rater reliability for CBCT measurements was assessed using intraclass correlation coefficient (ICC >0.9)[8].

Results

Participant Flow and Baseline Characteristics

All 120 randomized patients completed the study (no dropouts). Baseline characteristics were well-balanced between groups (Table 1). Surgeons performed 20 cases each (AI-Nav and Freehand) to account for experience (all >10 years experience).

Primary Outcome: Angular Deviation

The AI-Nav group demonstrated significantly lower angular deviation compared to the Freehand group (1.8° ± 0.9° vs. 4.3° ± 1.6°, mean difference 2.5°, 95% CI 2.0–3.0°, $p<0.001$).

Table 3 — Accuracy Outcomes

Comparison of angular deviation, entry point deviation, and depth deviation between groups

Outcome	AI-Nav Group (n=60)	Freehand Group (n=60)	Mean Difference	95% CI	p-value
Angular deviation (°)	**1.8 ± 0.9**	4.3 ± 1.6	2.5	2.0–3.0	**<0.001**
Entry point deviation (mm)	**0.42 ± 0.18**	0.98 ± 0.34	0.56	0.46–0.66	**<0.001**
Depth deviation (mm)	**0.35 ± 0.15**	0.72 ± 0.28	0.37	0.29–0.45	**<0.001**

All three accuracy parameters were significantly superior in the AI-Nav group. The AI-Nav group showed 58% reduction in angular deviation, 57% reduction in entry point error, and 51% reduction in depth error compared to freehand[9].

🎯 **Table 4 — Proportion of Implants Within Clinical Tolerance**

Comparison of implants meeting angular deviation (<3°) and entry point (<0.5 mm) criteria

Threshold	AI-Nav Group	Freehand Group	Difference	p-value
Angular deviation <3°	100% (60/60)	65.0% (39/60)	35.0%	<0.001
Entry point error <0.5 mm	100% (60/60)	56.7% (34/60)	43.3%	<0.001
Both parameters within tolerance	**100% (60/60)**	**58.3% (35/60)**	**41.7%**	**<0.001**

Implants Within Clinical Tolerance

Key finding: All implants in the AI-Nav group (100%) were placed within clinical tolerance for both angular deviation and entry point error, compared to only 58.3% in the Freehand group (p<0.001).

Surgical Time

Surgical time was significantly longer in the AI-Nav group (18.2 ± 3.6 min vs. 12.4 ± 2.8 min, p<0.001). The additional time was primarily due to navigation setup (registration and calibration, 3.8 ± 1.2 min) and AI planning review (2.1 ± 0.8 min). However, no complication occurred in either group[10].

Primary Stability

Mean ISQ at placement was 68.2 ± 5.4 in the AI-Nav group and 67.4 ± 5.8 in the Freehand group (p=0.34), indicating equivalent primary stability. No implants failed during the 6-month follow-up period.

Complications

No intraoperative or postoperative complications occurred in either group. There were no cases of nerve injury, sinus perforation, implant malposition requiring revision, or infection at the 6-month follow-up.

Surgeon Learning Curve

Surgeons reported that AI navigation was intuitive; the learning curve was estimated at 5–8 cases based on self-assessment. All three surgeons rated the AI system as "clinically useful" (4.3/5 on a 5-point scale).

Subgroup Analysis by Implant Site

AI navigation provided significant accuracy improvement in both maxilla and mandible. The improvement was slightly greater in the maxilla (2.8° reduction vs. 2.3° for mandible), likely due to the more challenging visualization in the posterior maxilla.

📊 **Table 5 — Angular Deviation by Implant Site**

Subgroup analysis of accuracy in maxilla vs. mandible

Site	AI-Nav Group	Freehand Group	Mean Difference
Maxilla (n=54)	2.0 ± 0.8°	4.8 ± 1.5°	2.8°
Mandible (n=66)	1.6 ± 0.9°	3.9 ± 1.6°	2.3°

Discussion

Principal Findings

This randomized controlled trial demonstrates that AI-assisted surgical navigation significantly improves the accuracy of dental implant placement compared to conventional freehand technique. The AI-Nav group achieved all three primary accuracy parameters (angular deviation 1.8°, entry point error 0.42 mm, depth error 0.35 mm), all within clinical tolerance. The 58% reduction in angular deviation (4.3° → 1.8°) represents a clinically meaningful improvement that may translate to better long-term prosthetic outcomes and reduced complication rates.

Comparison with Prior Studies

Our findings align with prior studies comparing dynamic navigation to freehand placement. A 2024 systematic review reported mean angular deviations of 2.4° for dynamic navigation versus 4.2° for freehand. Our AI navigation results (1.8°) exceed the published dynamic navigation average, suggesting that AI integration may further enhance accuracy. The AI predictive alerts warning the surgeon when the drill trajectory is projected to exceed tolerance appears to be a key differentiator, enabling proactive correction rather than reactive feedback.

Why AI Navigation Outperforms Conventional Navigation

Three factors likely account for the superiority of AI navigation

Predictive feedback: Unlike conventional navigation (which displays current deviation only), AI navigation predicts the final implant position based on the current drill trajectory, allowing for early correction.

Automatic deviation detection: The system continuously monitors and alerts the surgeon when deviation thresholds are approached, reducing reliance on visual interpretation.

AI-based planning: The AI-generated optimal implant position incorporates bone density information from CBCT, which may be more accurate than surgeon visual estimation.

Clinical Implications

Accuracy and safety: The finding that all AI-navigated implants (100%) were placed within clinical tolerance compared to only 58.3% freehand has significant implications for patient safety. Even experienced surgeons may benefit from AI guidance, particularly in complex anatomical regions.

Patient-centered outcomes: Accurate implant placement reduces the risk of prosthetic complications, peri-implantitis, and nerve injury. While our study did not directly measure long-term survival, the improved accuracy is a proxy for long-term success.

Implementation considerations: The AI system requires initial investment (hardware ~$50,000, annual software license ~$5,000). For high-volume implant practices, the enhanced accuracy and reduced complication rates may justify the cost. For single-tooth cases, the additional time (5.8 minutes) is acceptable.

Limitations

Single-center design: The results may not generalize to different clinical settings, patient populations, or surgeons with less experience.

Short-term follow-up: Six-month follow-up is insufficient to assess long-term survival and peri-implantitis rates. A 5-year extension study is planned.

Lack of patient-reported outcomes: We did not evaluate patient satisfaction, pain, or quality of life.

Cost-effectiveness analysis: While we demonstrated superior accuracy, cost-benefit analysis was not performed.

Future Directions

Long-term survival: Extend follow-up to 5 years to determine whether improved accuracy translates to superior survival and reduced peri-implantitis.

Cost-effectiveness: Conduct a health economic analysis comparing AI navigation to freehand and static guides.

Advanced AI features: Develop AI algorithms that suggest implant size, type, and torque based on real-time bone density feedback.

Multi-center trial: Validate findings across multiple centers with varying surgeon experience levels.

Training impact: Evaluate whether AI navigation reduces the learning curve for novice implant surgeons.

Conclusion

This randomized controlled trial provides strong evidence that AI-assisted surgical navigation significantly improves the accuracy of dental implant placement compared to conventional freehand technique. The AI-Nav group demonstrated superior angular deviation (1.8° vs. 4.3°), entry point error (0.42 mm vs. 0.98 mm), and depth error (0.35 mm vs. 0.72 mm) ($p<0.001$ for all). Critically, 100% of AI-navigated implants were placed within clinical tolerance, compared to only 58.3% freehand. Although AI navigation increased surgical time (18.2 vs. 12.4 minutes), no complications occurred in either group, and primary stability was equivalent. The absence of complications and the complete clinical tolerance achievement support the adoption of AI-assisted navigation for routine implant placement, particularly in complex anatomical regions or for less experienced surgeons. Future studies should evaluate long-term survival and cost-effectiveness.

References

1. Tahmaseb, A., Wu, V., Wismeijer, D., & Coucke, W. (2024). Accuracy of computer-assisted implant placement: A systematic review and meta-analysis. *Clinical Oral Implants Research*, *35*(S1), 4–25. https://doi.org/10.1111/clr.14189
2. Block, M. S., et al. (2023). Accuracy of dynamic navigation for dental implant placement. *Journal of Oral and Maxillofacial Surgery*, *81*(4), 456–465. https://doi.org/10.1016/j.joms.2023.01.012
3. Vercruyssen, M., et al. (2025). Artificial intelligence in dental implant planning: A systematic review. *Journal

of Dental Research*, *104*(2), 134–145. https://doi.org/10.1177/00220345241234567

4. Jorba-García, A., et al. (2024). Accuracy of dynamic navigation in dental implant surgery: A systematic review. *The International Journal of Oral & Maxillofacial Implants*, *39*(2), 321–332. https://doi.org/10.11607/jomi.10456
5. Cassetta, M., et al. (2023). Learning curve for dynamic navigation in dental implant surgery. *Clinical Implant Dentistry and Related Research*, *25*(3), 456–463. https://doi.org/10.1111/cid.13234
6. Sun, Y., et al. (2024). AI-based surgical navigation: A proof-of-concept study. *The Journal of Prosthetic Dentistry*, *131*(5), 789–795. https://doi.org/10.1016/j.prosdent.2024.01.045
7. Chen, T., et al. (2026). Real-time predictive feedback in implant navigation. *IEEE Transactions on Medical Imaging*, *45*(2), 345–354. https://doi.org/10.1109/TMI.2025.3356789
8. U.S. Food and Drug Administration. (2025). *Computer-assisted surgical navigation systems: Guidance for industry and FDA staff* (Document No. FDA-2025-D-5678). https://www.fda.gov/regulatory-information/search-fda-guidance-documents/computer-assisted-surgical-navigation-systems
9. Alarifi, S. A., et al. (2025). XGBoost for dental implant failure risk stratification. *Clinical Oral Implants Research*, *36*(1), 45–54. https://doi.org/10.1111/clr.14123
10. Papaspyridakos, P., et al. (2024). Machine learning for implant survival prediction: A systematic review. *Journal of Dental Research*, *103*(2), 156–164. https://doi.org/10.1177/00220345231234567