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ORIGINAL PAPER

Robotic Guidance and Optical Navigation for Precision Implant Placement: a Prospective Comparative Clinical Study

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ABSTRACT

Background: *Accurate three-dimensional implant positioning is essential for prosthetically driven implant dentistry and for reducing the risk of injury to adjacent anatomical structures.*

Methods: *This prospective randomized comparative study included 180 adults requiring single delayed implant placement, who were assigned to robotic-guided (RG) surgery (n=60), optical dynamic navigation-guided (ONG) surgery (n=60), or conventional freehand (CF) surgery (n=60) groups. Preoperative and postoperative cone-beam computed tomography (CBCT) datasets were superimposed to measure angular, apical, coronal and depth deviations between planned and actual implant positions. Secondary outcomes included operative time, postoperative pain, six-month satisfaction and early complications.*

Results: *The final analysis included 176 patients. The mean angular deviation was the lowest in the RG group (1.82°±0.64°), followed by ONG (2.34°±0.89°) and CF groups (4.87°±1.53°; p<0.001). Apical and coronal deviations showed the same pattern. Robotic-guided surgery required longer surgical time than ONG and CF, but early complications were less frequent in RG (3.4%) and ONG (6.8%) than CF (15.5%; p=0.042).*

Conclusion: *Within the limitations of a single-center study and short follow-up, RG achieved the highest placement accuracy, while dynamic optical navigation provided clinically meaningful improvement over freehand placement. Long-term survival, prosthetic outcomes and cost-effectiveness require further evaluation.*

Keywords: dental implants, robotic computer-assisted implant surgery, dynamic navigation, optical navigation, CBCT, guided implant placement, implant accuracy.

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INTRODUCTION

While osseointegration is an important factor for long-term functional and esthetic success of dental implant therapy, the three-dimensional position of the implant is also prosthetically correct and essential for long-term success (1, 2). Malposition can affect emergence profile, screw-access location, interimplant spacing, peri-implant tissue stability and safety margin around the mandibular canal, maxillary sinus, nasal floor and adjacent roots (3, 4).

The first manuscript contained several accurate numerical statements which were not backed up by the cited articles. The statements have been reworded to be more conservative and in line with the literature. Systematic reviews suggest that computer-assisted implant surgery (CAIS) with static guides, dynamic navigation and robotic surgery generally decreases planned-to-placed implant deviations from unguided freehand placement, but the amount of decrease is dependent on study design, clinical site, arch, tooth support, operator experience and measurement protocol (3-6).

Static computer-assisted surgery is a technique that involves creating a surgical guide to take the virtual implant plan to the operative field. This method provides physical guidance but it may be influenced by segmentation error, guide design, printing or milling error, guide seating, sleeve tolerance, limited irrigation and limited intraoperative flexibility (7, 8). Some of these limitations can be addressed by dynamic navigation systems which rely on optical tracking, fiducial registration and real-time visual feedback, while enabling the surgeon to adjust the plan during surgery (9-11). Drilling is still a manual process, so the dynamic navigation accuracy is still affected by hand stability, visual attention, calibration quality and learning curve (9, 12).

Robotic CAIS is a new development of digitally guided implant surgery. Depending on the platform, contemporary robotic systems can offer the haptic constraint, semi-autonomous positioning or task-autonomous drilling. When appropriate, the term robotic CAIS is used rather than the less precise term 'robotic-assisted surgical systems' (13-16). Recent clinical studies with both randomized and retrospective design indicate that robotic systems can enhance the positional accuracy over freehand placement and may decrease the operator-dependent variations, but the clinical significance of the small differences between robotic and dynamic navigation systems is still being evaluated (15-17).

Based on this, the present prospective comparative study was conducted to compare robotic-guided (RG), optical dynamic navigation-guided (ONG) and conventional freehand (CF) surgery implant placement in a single clinical population with a cone-beam computed tomography (CBCT)-based deviation analysis. The main goal was to evaluate the differences in angular, apical, coronal and depth deviations from the planned implant position. Secondary outcomes included operative time, postoperative pain, patient satisfaction and early complications. The working hypothesis was that robotic guidance would have a lower positional deviation than optical navigation and freehand surgery and dynamic navigation would be more accurate than freehand placement. ❑

MATERIALS AND METHODS

Study design and ethical approval

This prospective randomized comparative clinical study was conducted in the Department of Oral and Maxillofacial Surgery, University Dental Hospital, from March 2021 to September 2023. Ethical approval was obtained from the Institutional Ethics Committee before patient enrollment. The present study followed the Declaration of Helsinki and all participants provided their written informed consent before CBCT imaging and surgical intervention.

Study population

Adults aged 18-70 years requiring a single delayed implant in the maxilla or mandible were screened. Inclusion criteria comprised adequate bone volume for the planned implant without simultaneous augmentation; plaque control compatible with surgery; American Society of Anesthesiologists (ASA) physical status I or II; and ability to undergo CBCT imaging. Oral hygiene was assessed using the Silness and Loe plaque index and only patients with plaque scores compatible with good plaque control were included. Periodontal status was screened using the 2017

World Workshop classification and patients with untreated periodontitis, active periodontal pockets requiring therapy, or suppuration were excluded.

Exclusion criteria were uncontrolled diabetes mellitus (HbA1c >7.0%), cardiovascular instability, heavy smoking (>10 cigarettes/day), pregnancy or lactation, previous head-and-neck radiotherapy, need for guided bone regeneration at the implant site, immediate implant placement and inability to provide valid informed consent.

Sample size, randomization, and blinding

Sample size was calculated using G*Power 3.1, assuming a moderate effect size of 0.4 for angular deviation, alpha error of 0.05 and power of 85%. A minimum of 51 participants per group was required; after allowing for approximately 15% attrition, 60 participants were recruited *per* group. Eligible participants were randomized into the three RG, ONG, CF groups using a computer-generated sequence and sealed opaque envelopes. Cone-beam computed tomography outcome assessors were blinded to group allocation.

Preoperative planning

All participants underwent standardized preoperative CBCT scanning with a voxel size of 150 micrometers. DICOM datasets were imported into implant planning software and virtual implant positions were planned according to prosthetically driven principles. Two calibrated investigators finalized the plan and calibration agreement was recorded before study initiation. Implant dimensions were selected according to the available bone envelope and prosthetic requirement (Figure 1).

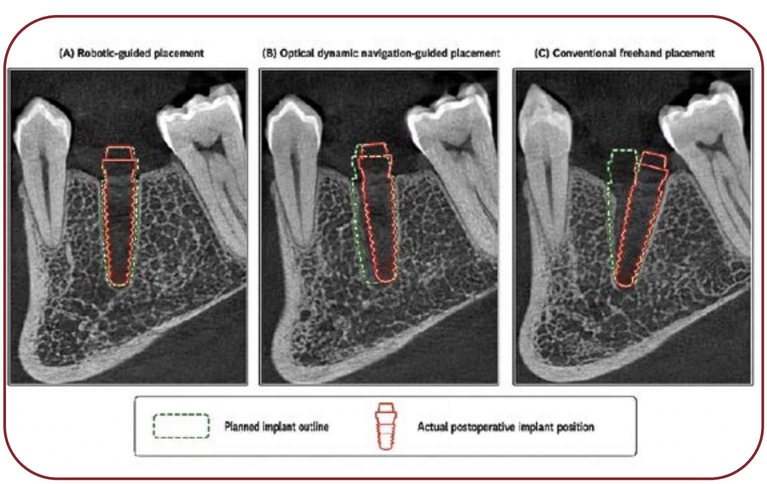

FIGURE 1. Representative CBCT-based superimposition of planned and postoperative implant positions should be inserted here as three matched panels: (A) robotic-guided placement; (B) optical dynamic navigation-guided placement; and (C) conventional freehand placement

Surgical protocols

In the RG group, robotic CAIS was performed using a haptic robotic implant guidance system after patient tracker stabilization, fiducial/anatomical landmark registration and system calibration. The system provided real-time guidance and haptic limitation of drill deviation from the planned trajectory. In the ONG group, a dynamic optical navigation system was used after tracker placement and calibration; the surgeon manually aligned the tracked handpiece to the virtual plan using real-time visual feedback. In the CF group, implants were placed using conventional clinical judgment based on the preoperative plan and anatomical landmarks, without intraoperative tracking or guide-based constraint.

All surgeries were performed under local anesthesia by calibrated surgeons with more than five years of implant experience and formal training on the digital systems used in the study. The same implant system and standard postoperative protocol were used across groups.

Outcome measurements

Postoperative CBCT scans were obtained 7-10 days after surgery using the same acquisition protocol as the preoperative scan. Planned and achieved implant positions were compared after surface-based registration. Primary outcomes were angular deviation, apical deviation, coronal/platform deviation and depth deviation. Secondary outcomes were surgical duration, intraoperative complications, visual analog scale (VAS) pain score at 24 hours and seven days, patient satisfaction at six months and early complications up to three months.

Statistical analysis

Data were analyzed using SPSS version 28.0. Continuous variables were summarized as mean±standard deviation (SD) and compared using one-way ANOVA followed by Tukey post-hoc tests. Categorical variables were summarized as frequency and percentage and compared using chi-square or Fisher exact tests, as appropriate. A two-tailed p value <0.05 was considered statistically significant. Intention-to-treat principles were applied where follow-up data were available. ❑

RESULTS

Baseline characteristics

Among 198 screened participants, 180 met the criteria and were randomized. Four participants were lost to follow-up, leaving 176 subjects in the final analysis: RG n=59, ONG n=59 and CF n=58. Baseline age, sex distribution, jaw location, bone density, bone dimensions and ASA status were comparable across groups (Table 1).

Primary accuracy outcomes

Robotic guidance demonstrated the lowest deviations across all primary accuracy variables (Table 2). The mean angular deviation was 1.82° ± 0.64° in the RG group, 2.34° ± 0.89° in the ONG one and 4.87° ± 1.53° in the CF group (p<0.001). Apical, coronal and depth deviations showed the same hierarchy, with all pairwise comparisons remaining statistically significant.

Secondary outcomes

Mean surgical duration was longest in the RG group, followed by the ONG and CF groups (Table 3). A learning effect was observed for digitally guided procedures, particularly RG, where the mean duration decreased from 48.2±9.3 minutes in the first 20 cases to 38.1±6.4 minutes in the last 20 cases. Pain scores and satisfaction favored the guided groups, while early complications were most frequent in the CF group. ❑

DISCUSSION

The main result was that the mean angular, apical, coronal and depth deviations of robotic CAIS were the lowest, followed by optical

Parameter	RG (n=59)	ONG (n=59)	CF (n=58)	p value
Age (years), mean ± SD	47.2 ± 11.8	46.7 ± 13.1	46.5 ± 12.2	0.934
Female, n (%)	34 (57.6)	33 (55.9)	31 (53.4)	0.842
Maxillary site, n (%)	37 (62.7)	35 (59.3)	34 (58.6)	0.756
Mandibular site, n (%)	22 (37.3)	24 (40.7)	24 (41.4)	0.756
Bone density (HU), mean ± SD	648.3 ± 124.7	652.1 ± 131.2	641.8 ± 118.9	0.887
Bone width (mm), mean ± SD	8.42 ± 1.23	8.38 ± 1.19	8.51 ± 1.31	0.842
Bone height (mm), mean ± SD	12.84 ± 1.67	12.91 ± 1.72	12.76 ± 1.58	0.901
ASA I / II, n	43 / 16	42 / 17	41 / 17	0.923

SD: standard deviation; ONG: optical dynamic navigation-guided; CF: conventional freehand; RG: robotic-guided; ASA: American Society of Anesthesiologists

TABLE 1. Baseline demographic and clinical characteristics

Parameter	RG (n=59)	ONG (n=59)	CF (n=58)	p value
Angular deviation (°), mean ± SD	1.82 ± 0.64	2.34 ± 0.89	4.87 ± 1.53	<0.001
Angular deviation range (°)	0.65-3.42	0.89-4.73	2.14-8.52	-
Apical deviation (mm), mean ± SD	0.48 ± 0.23	0.73 ± 0.38	1.84 ± 0.76	<0.001
Coronal/platform deviation (mm), mean ± SD	0.52 ± 0.31	0.81 ± 0.42	2.13 ± 0.91	<0.001
Depth deviation (mm), mean ± SD	0.31 ± 0.18	0.47 ± 0.29	0.89 ± 0.52	<0.001

SD: standard deviation; RG: robotic-guided; ONG: optical dynamic navigation-guided; CF: conventional freehand

TABLE 2. Primary outcome measures: planned-to-placed implant deviation

Parameter	RG (n=59)	ONG (n=59)	CF (n=58)	p value
Surgical duration (minutes), mean ± SD	42.3 ± 8.7	38.6 ± 7.2	28.4 ± 6.1	<0.001
VAS pain score at 24 hours, mean ± SD	3.2 ± 1.4	3.6 ± 1.6	4.1 ± 1.8	0.014
VAS pain score at seven days, mean ± SD	1.4 ± 0.9	1.7 ± 1.1	2.3 ± 1.3	<0.001
Satisfaction score at six months, mean ± SD	9.2 ± 0.8	8.7 ± 1.1	8.1 ± 1.3	<0.001
Intraoperative complications, n (%)	1 (1.7)	2 (3.4)	5 (8.6)	0.128
Early complications at three months, n (%)	2 (3.4)	4 (6.8)	9 (15.5)	0.042
Early implant mobility/failure, n (%)	0 (0)	0 (0)	2 (3.4)	-

SD: standard deviation; RG: robotic-guided; ONG: optical dynamic navigation-guided; CF: conventional freehand; VAS: visual analog scale

TABLE 3. Secondary outcomes: surgical parameters, patient-reported outcomes and complications

dynamic navigation, while CF placement had the highest deviation. These results are consistent with recent randomized clinical studies and systematic reviews that have shown that the accuracy of implant placement is better with robotic and navigation systems than with freehand placement (3, 5, 13, 15, 17).

The superior performance of the RG group could be attributed to the use of digital planning, optical registration, real-time positional tracking and haptic or robotic constraint. Robotic navigation can minimize deviation from the planned drill path by restricting handpiece motion from outside the planned spatial envelope, as opposed to purely visual dynamic navigation. The clinical studies of the haptic and robot-assisted systems have reported good positional accuracy (13-17).

The ONG group achieved a higher accuracy than CF without compromising on the flexibility during the operation. This is in line with the literature on dynamic navigation, which states that real-time tracking and visual feedback are benefits over freehand surgery (9-12). However, the surgeon is still responsible for interpreting the feedback from the monitor and moving his hands. Calibration error, patient tracker movement, drill tracking error, limited mouth opening, blood and saliva interference, operator attention and learning curve effects can therefore cause residual error (9, 10, 12).

The CF group shows the greatest deviations and ranges, which does not mean that freehand implant placement is clinically unacceptable in all cases but rather that it is more operator dependent and may be less predictable in cases where precise angulation or proximity to critical anatomical structures is required. This point was reworded due to the use of unsupported threshold statements and articles that did not mention the information.

Improved accuracy has to be interpreted with caution in the clinical context. Statistically significant differences in angular or linear deviation may not be clinically significant, especially in simple single tooth sites with sufficient bone volume. On the other hand, higher accuracy can be of great importance in esthetic zone implants, narrow ridges, posterior mandible locations near the inferior alveolar canal, maxillary posterior locations near the sinus, and cases in which the implant is to be retained by screws and the prosthetic emergence is required. Recent comparative studies have focused on the need to understand accuracy in conjunction with the operating time, patient safety, prosthetically restorable, training needs and system cost (15-17).

The longer operating time in the RG group is clinically relevant. The time was probably extended due to tracker placement, registration, calibration and system checks. However, the reduction in surgical time in later cases indicates a learning curve. The same can be said for dynamic navigation and robotic surgical workflows, where efficiency increases with repeated use and team familiarization (9, 12, 17).

The digitally guided groups were more satisfied with the patient reported outcomes, with the greatest satisfaction being noted in RG subjects. The results are secondary and exploratory, as patient satisfaction is affected by patient expectations, chair side communication, postoperative discomfort and perceived technological sophistication. Further follow-up is required to assess if the increased accuracy of implant placement leads to greater peri-implant tissue stability, fewer complications with the prostheses or greater implant survival.

The decrease in early complications in guided groups is possible since better control of the osteotomy trajectory might decrease the damage to surrounding structures and corrective manipulation. However, the present study was not designed to be powered for complication outcomes and rare events need larger multicenter trials. Hence, statements of safety superiority were made with a soft touch and as preliminary results.

The present study has some limitations. Firstly, it was conducted in a single center, which may reduce the generalizability of its findings. Secondly, follow-up was brief and limited to early results, not long-term survival, marginal bone loss or prosthetic complications. Thirdly, immediate implants, full arch rehabilitation, augmented ridges, zygomatic implants or fully edentulous jaws were not included in the study. Fourthly, the results are also platform-dependent and might not be applicable to all robotic and navigation platforms. Lastly, cost-effectiveness was not evaluated and economic assessment is needed before generalizing the adoption of the program.

Multicenter randomized trials with longer follow-up, standardized methods for measuring deviation, validated patient-reported outcome measures and economic analyses should be included in future research. Comparative studies should also assess the accuracy of the effect of arch type, edentulous span, implant position, operator experience, mouth opening and guide or tracker stability. This evidence will help to establish when robotic CAIS provides clinically meaningful benefits over dynamic navigation, static guides and freehand surgery. ❑

CONCLUSION

Robotic computer-assisted implant surgery achieved the greatest positional accuracy in this prospective comparative study, while optical dynamic navigation also improved accuracy compared with conventional freehand placement. Robotic guidance was associated with longer surgical duration, but early complications and patient-reported outcomes favored the guided groups. These findings support the selective clinical use of advanced guidance systems in anatomically demanding or prosthetically critical implant cases, while emphasizing the need for long-term follow-up and cost-effectiveness data before broad generalization. ❑

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