THE JOURNAL OF PROSTHETIC DENTISTRY

CLINICAL RESEARCH

Accuracy comparison of 3D printed tooth-supported implant surgical guides: A prospective observational clinical study

Alireza Rezaei, DDS,[a] Farnoush Fotovat, DDS, MSD,[b] Ali Heidari, DDS, MSD,[c] Zahra Khayami, DDS, MSD,[d] Zahra Khalafi, DDS, MSD,[e] and Loghman Rezaei-Soufi, DDS, MSD[f]

ABSTRACT

Statement of problem. Implant-supported prostheses provide a reliable method of replacing missing teeth. To avoid complications, their accurate placement is critical. Advances in static computer-aided implant surgery (sCAIS), which uses 3-dimensional (3D) imaging and printing, have improved implant placement accuracy. However, whether the location of supporting teeth (anterior versus posterior; maxilla versus mandible) influences accuracy has not been fully explored.

Purpose. The purpose of this prospective observational clinical study was to assess the accuracy of 3D printed, tooth-supported implant surgical guides in both the anterior and posterior regions of the maxilla and mandible.

Material and methods. A total of 67 participants (116 implants) were included, with preoperative cone beam computed tomography (CBCT) and intraoral scans used to plan implant positions. Printed surgical guides were used for implant placement, and deviations (entrance, apical, depth, and angular) were measured postoperatively. Implant deviations were analyzed using mixed-effects models with patient intercepts and Holm–Bonferroni–adjusted tests.

Results. No significant differences in accuracy were found between the anterior and posterior regions or between the maxilla and mandible (P>.05). The mean deviations were similar across entrance, apical, depth, and angular parameters. Apical deviation exhibited the highest inaccuracy, while depth deviation showed the least variation across all regions. The maxilla showed the most notable deviation in the mesiobuccal direction and the least deviation in the mesiolingual direction (P=.029), while other regions showed no statistically significant differences (P>.05).

Conclusions. Printed, tooth-supported implant surgical guides demonstrated high accuracy across all regions, with apical deviation as the main source of inaccuracy. (J Prosthet Dent 2026;136:127-135)

Implant-supported prostheses have been a well-established and reliable method of replacing missing teeth, with demand increasing in both younger and older populations because of factors such as systemic diseases, poor oral hygiene, dietary changes, and irregular dental visits.[1] However, implant placement is sensitive, and improper positioning can lead to complications such as damage to surrounding structures, esthetic issues, inflammation, and even implant failure.[2] Consequently, accurate examination and treatment planning are crucial for successful outcomes.[3] Advances in static computer-aided implant surgery (sCAIS) have significantly improved the precision of implant placement.[4] sCAIS uses 3D data from cone beam computed tomography (CBCT), surface scanning, computer-aided design and computer-aided manufacturing (CAD-CAM), and digital 3-dimensional (3D) printing. With this technology, clinicians can virtually plan an implant to meet prosthetic needs while ensuring proper orientation and avoiding damage to vital structures like nerves and blood vessels.[5,6]

Three-dimensional printing has revolutionized implant surgery by enabling the design and production of surgical guides that regulate implant position, angle, and

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
The authors have no conflict of interest to declare.

[a]Graduate student, Department of Oral Surgery and Implantology, Carolinum, Goethe University, Frankfurt, Germany.
[b]Assistant Professor, Department of Prosthodontics, School of Dentistry, Dental Research Center, Hamadan University of Medical Sciences, Hamadan, Iran.
[c]Assistant Professor, Department of Oral and Maxillofacial Surgery, School of Dentistry, Dental Research Center, Hamadan University of Medical Sciences, Hamadan, Iran.
[d]Assistant Professor, Department of Restorative Dentistry, School of Dentistry, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran.
[e]Assistant Professor, Department of Restorative, School of Dentistry, Dental Research Center, Hamadan University of Medical Sciences, Hamadan, Iran.
[f]Professor, Department of Restorative, School of Dentistry, Dental Research Center, Hamadan University of Medical Sciences, Hamadan, Iran.

Clinical Implications

Three-dimensionally printed, tooth-supported surgical guides were found to provide consistent and reliable accuracy for implant placement in all jaw regions. Greater apical deviation highlighted the need for careful planning, but, overall, these guides enabled safe and precise implant surgery across various clinical situations.

drilling path.[7] These guides have been based on the patient's bone, mucosa, and teeth.[8,9] By providing a more comprehensive 3D visualization of the bone and surrounding tissues before surgery, these guides not only facilitate precise implant placement but also reduce treatment time, recovery time, and postoperative pain.[10] Several factors, including the fixation stability, guide type, and implant insertion technique, can influence the accuracy of sCAIS.[11,12] The location of the supporting teeth, whether in the anterior or posterior region and whether in the maxilla or mandible, is an often overlooked factor influencing accuracy. A few prior studies have examined the accuracy of sCAIS,[13–15] with some specifically comparing the accuracy of sCAIS across different regions.[16–22] However, further investigation into this topic remains necessary to enhance understanding and optimize clinical outcomes.

Accuracy includes both trueness and precision, as specified by the International Organization for Standardization (ISO) 5725–1:2023 standard.[23] Trueness refers to the deviation between the actual postoperative implant position and the planned preoperative location, while precision refers to the consistency of implant placement in repeated tests. While accuracy typically refers to trueness in clinical studies, both trueness and precision have been commonly assessed in laboratory experiments.[23] This study focused primarily on evaluating trueness, with indicators such as coronal deviation, apical deviation, depth or vertical deviation, and angular deviation.

The aim of this study was to evaluate the accuracy of printed, tooth-supported implant surgical guides in the anterior and posterior regions of the maxilla and mandible. The null hypotheses were that no significant differences would be found in the accuracy of printed, tooth-supported implant surgical guides between the anterior and posterior regions and between the maxilla and mandible.

MATERIAL AND METHODS

This prospective observational clinical study was approved by the Research Ethics Committees of Hamadan University of Medical Sciences (IR.UMSHA.REC.1402.559) and registered at the Iranian Registry of Clinical Trials (IRCT20240223061089N1). All participants gave their informed consent after being informed about the procedure and the study. Individuals were eligible for inclusion if they were at least 18 years of age, had 1 to 3 missing teeth in the edentulous area, and presented with sufficient bone quality and quantity to allow for the placement of implants with a diameter of at least 3.5 mm and a length of at least 8.5 mm. Additionally, tooth extractions had to be completed at least 3 months before enrollment, and patients were required to be classified as American Society of Anesthesiologists (ASA) Class I or II in terms of medical status. Patients were excluded if they were pregnant, heavy smokers (≥20 pack-year smoking history), or required bone augmentation or sinus lift procedures. Those with physical or psychological conditions that could interfere with implant surgery were also excluded, including individuals undergoing radiotherapy or chemotherapy or those receiving bisphosphonate treatment. Other exclusion criteria included the presence of uncontrolled systemic diseases and limited mouth opening, which would have prevented the use of a surgical guide, as detailed in Table 1. As a prospective clinical study that included all consecutive patients meeting the inclusion criteria, no a priori sample size calculation was performed. Post hoc power analysis, based on the observed differences, indicated an achieved statistical power of approximately 0.53 for anterior-posterior entrance deviations and 0.59 for maxillary–mandibular depth deviations (α=.05), suggesting limited sensitivity to detect small to moderate effect sizes. An estimated sample size of approximately 140 implants per group would be required to attain 80% power for comparable analyses.

After initial clinical screening, preoperative cone beam computed tomography (CBCT) scans (3D Accuitomo;

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
18 years old and older	Pregnant women
1 to 3 missing teeth in each edentulous area	Heavy smokers (≥20 pack-year smoking history)
Sufficient bone quality and quantity to insert an implant of ≥Ø3.5 mm and ≥8.5 mm in length	Patients requiring bone augmentation or sinus lift
Extractions performed at least 3 months earlier	Physical or psychological disorders prohibiting implant surgery: patients undergoing radiotherapy or chemotherapy, receiving bisphosphonates
Stable medical condition to undergo implant surgery (ASA 1 or 2)	Uncontrolled systemic disease
	Limited mouth opening (impossibility of using surgical guide)

ASA, American Society of Anesthesiologists.

Morita) were carried out to verify the presence of sufficient bone volume for implant insertion without the need for bone augmentation. The CBCT scans were performed with the following settings: 90 kVp, 5 mA, 18 seconds, 0.25×0.25×0.25-mm voxel size, 8×8-cm FOV (medium field of view), with the patient's Camper plane (ala-tragus) parallel to the horizontal plane. The data were converted into Digital Imaging and Communications in Medicine (DICOM or DCM) format. Surface scanning was performed using an intraoral scanner (TRIOS 4; 3Shape A/S). The DCM file from the CBCT examination and the standard tessellation language (STL) file from the intraoral surface scan were imported and merged in a software program (3Shape Implant Studio; 3Shape A/S). A single qualified surgeon (A.R.) performed all virtual implant planning. The prosthesis design and the determination of the surrounding anatomic structures were completed in the software program to determine implant length, diameter, and optimal position. The surgical guides were fabricated with a Formlabs 2 Stereolithography (SLA) printer and a biocompatible resin material (Dental SG; Formlabs). A material thickness of 3 mm and a guide-to-teeth offset of 0.15 mm were used for all guides. All laboratory processes were performed by a single standardized dental laboratory. All guides were tooth-supported and designed without metallic sleeves. The insertion bore was matched to the drill-shank diameter, providing both lateral guidance and depth control throughout the drilling sequence, thereby eliminating sleeve–bur clearance (Figs. 1 and 2).

One experienced surgeon (A.R.) inserted 116 bone-level implants (Ø3.5 to 4.5×8.5 to 13 mm) (AnyOne; MegaGen) in 67 patients using flapless, minimally invasive techniques under local anesthesia (2% lidocaine with epinephrine). Resonance frequency analysis (RFA), assessed as the implant stability quotient (ISQ), insertion torques were measured, and healing abutments were placed. A mouthwash solution (0.2% chlorhexidine twice a day for 2 weeks), antibiotic (1 g amoxicillin twice a day for 5 days), and analgesic (400 mg ibuprofen, 1 to 4 times a day as needed) were prescribed after surgery.

Implant placement accuracy was assessed using 2 DCM-format files: the preoperative planned position and the postoperative position with scan bodies in place. Both scans were captured using an intraoral scanner (TRIOS 4; 3Shape A/S), and a software program (3Shape Dental System; 3Shape A/S) was used to compare the planned and actual implant positions, quantifying placement accuracy. Four deviation parameters between the planned and placed implant positions were evaluated. The global entrance deviation is the linear distance between the coronal centers of the planned and placed implants. The global apical deviation is the linear distance between the apical centers of the planned and placed implants. The depth deviation is the vertical distance between the apical centers of the planned and placed implants. Positive values (+) indicate deeper positions, while negative values (–) indicate shallower positions. The angular deviation is the angle formed by the long axes of the planned and placed implants (Fig. 3). For standardization, apical deviations were measured at 8 mm from the entrance, despite implant lengths ranging from 8.5 to 13.5 mm. Figures 4 and 5

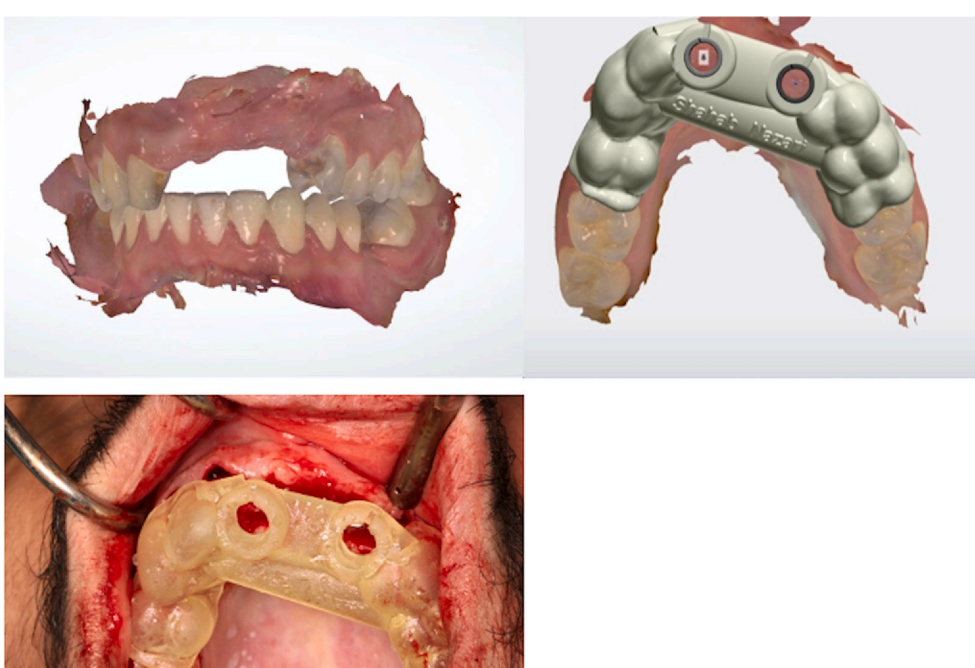

Figure 1. Implant placement with surgical guide in anterior region.

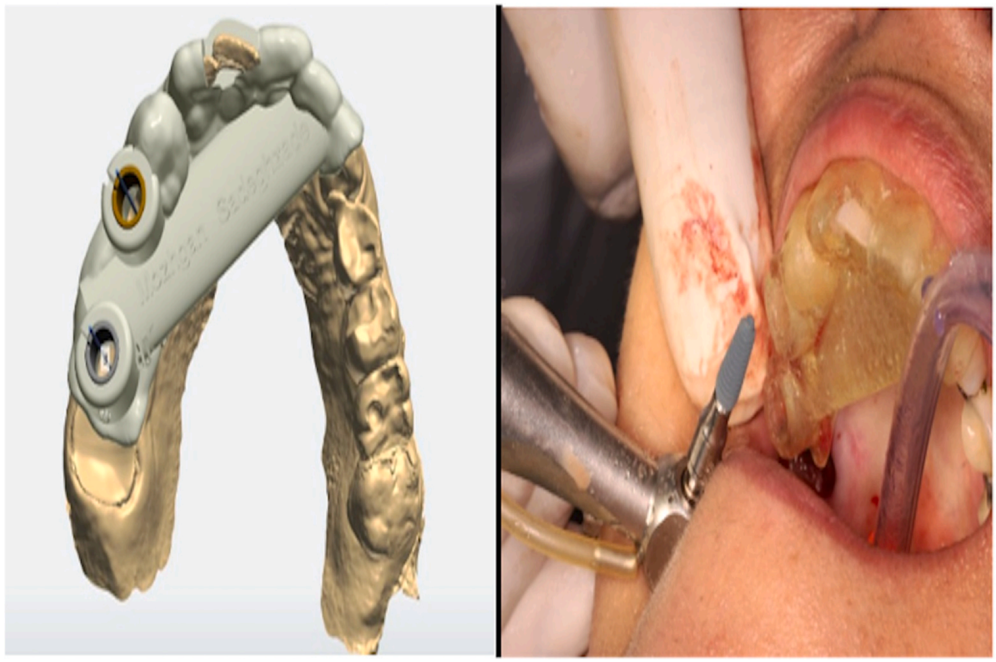

Figure 2. Implant placement with surgical guide in posterior region.

illustrate deviations in the anterior and posterior regions, respectively, using a software program (3Shape Dental System; 3Shape A/S).

Given that some patients received multiple implants, mixed-effects models with a patient-level random intercept were applied to account for within-patient correlations when comparing anterior versus posterior and maxilla versus mandible for entrance, depth, and angular deviations. To account for the potential non-independence of measurements arising from multiple implants placed in the same patient, all implant-level comparisons were analyzed using linear mixed-effects models with patient as a random intercept. Fixed effects

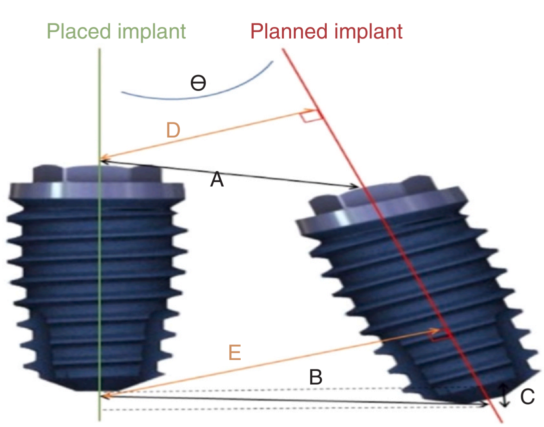

Figure 3. Definition of deviation types between placed and planned implant: A, Global entrance (coronal) deviation. B, Global apical deviation. C, Depth deviation. D, Horizontal entrance (coronal) deviation. E, Horizontal apical deviation. θ, Angular deviation.

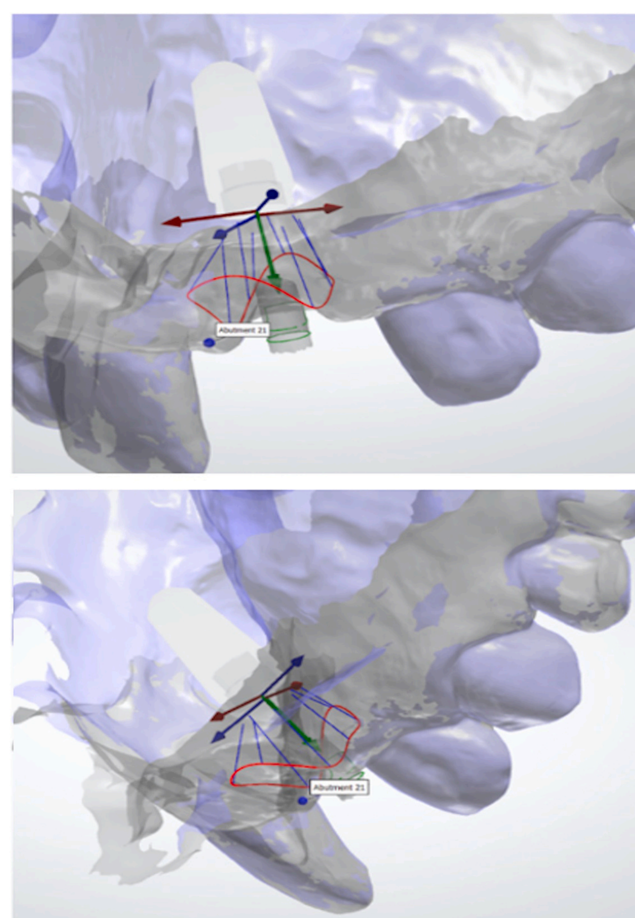

Figure 4. Measuring the amount of error in the anterior region in the 3Shape dental system software program.

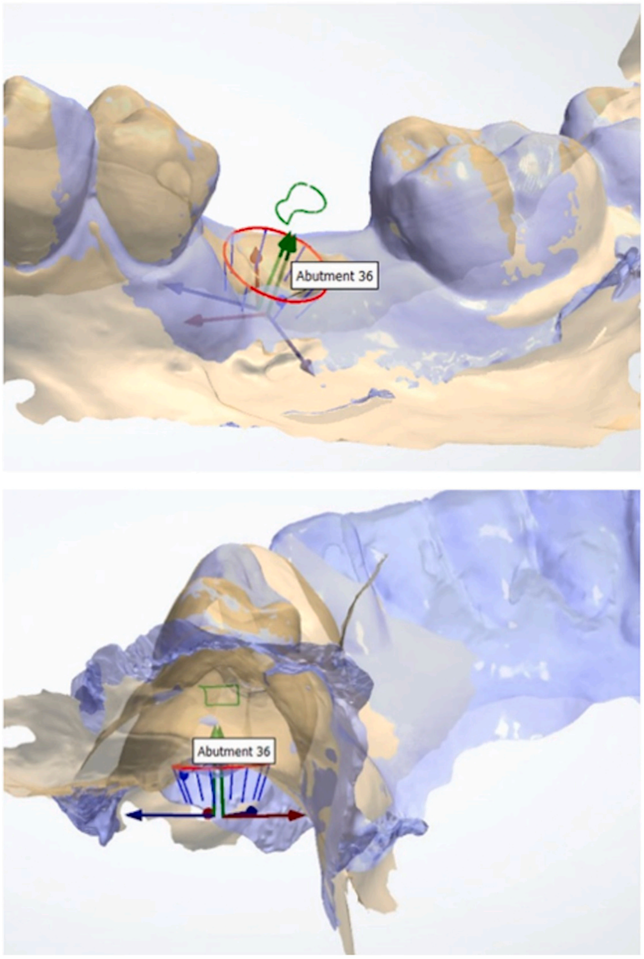

Figure 5. Measuring the amount of error in the posterior region in the 3Shape dental system software program.

included region (anterior and posterior) and jaw (maxilla and mandible), as appropriate for each comparison. Model residuals were inspected to confirm normality and homoscedasticity. *P* values were obtained using the Satterthwaite approximation for degrees of freedom, and a Holm-Bonferroni correction was applied across the set of comparisons to control the family-wise error rate. To assess the normality of the data distribution for direction of implant deviation in entrance and apex, between planned and actual implant positions, both the Shapiro-Wilk and Kolmogorov-Smirnov tests were applied. In cases of disagreement between the 2 tests, the Shapiro-Wilk test was prioritized. For normally distributed data, parametric tests such as analysis of variance (ANOVA) were used, whereas nonnormally distributed data were analyzed using nonparametric methods, including the Kruskal-Wallis test. Descriptive data are presented as mean ±standard deviation (SD) (α=.05 after correction). Analyses were performed in a statistical software program (IBM SPSS Statistics for Windows. v23.0; IBM Corp and R v4.3.2 lme4 and lmerTest packages; The R Project for Statistical Computing).

RESULTS

A total of 67 participants (31 women and 36 men; age 31 to 62 years) received 116 bone-level implants in edentulous regions using a printed surgical guide. After the Holm-Bonferroni correction, the mean entrance deviation was statistically similar in the anterior and in the posterior region (0.50 ±0.41 mm and 0.37 ±0.25 mm) (*P*>.05). Similarly, no substantial variations were noted (*P*>.05) between anterior and posterior implants regarding apical (0.74 ±0.41 mm and 0.67 ±0.32 mm, *P*=.244), depth (0.42 ±0.55 mm and 0.29 ±0.49 mm, *P*=.255), or angular deviation (1.90 ±1.52 and 1.83 ±1.67 degrees, *P*=.573). A post hoc power analysis indicated limited sensitivity: power was approximately 0.53 (Cohen d approximately 0.38) for entrance deviation between anterior and posterior regions, and approximately 0.59 (Cohen d approximately 0.45) for depth deviation between maxilla and mandible. These values suggest that nonsignificant findings should be interpreted cautiously. The mean entrance deviation was 0.44 ±0.37 mm in the maxilla and 0.42 ±0.25 mm in the mandible (*P*=.764). Apical deviation was 0.71 ±0.40 mm and 0.69 ±0.26 mm, respectively (*P*=.669). Depth deviation was greater in the maxilla (0.42 ±0.53 mm) than in the mandible (0.19 ±0.47 mm), reaching significance in the mixed-effects model (*P*=.025) but not after the Holm-Bonferroni correction (*P*=.198). Angular deviation showed no difference between the maxilla (1.85 ±1.59 degrees) and mandible (1.91 ±1.62 degrees) (*P*=.904). Overall, no significant interarch differences were found (Table 2). In addition, more positive values (indicating deeper implant positions) were observed for depth deviation across all regions. In all regions, the depth deviations were lowest, while apical deviations showed the highest values between linear deviations (Fig. 6). Directional deviations in entrance and apex were compared (Table 3). In the maxilla, both entrance and apical deviations showed significant variation (*P*=.029). The greatest entrance deviation occurred in the mesiobuccal (MB) direction, and the smallest in the mesiolingual (ML) direction. At the apex, the largest deviation was also in the MB direction and the smallest in the ML direction. In the mandible, deviations were not significantly different (*P*>.05). Similar directional variations were observed in the anterior and posterior regions and were not statistically significant (*P*>.05).

DISCUSSION

Using implant surgical guides has been reported to significantly improve the accuracy and predictability of dental implant placement by ensuring precise positioning relative to adjacent teeth and anatomic structures.[5] Nonetheless, errors may still arise at various stages of the digital

Table 2. Mean ±standard deviation values for entrance, apical, depth, and angular deviation between planned and actual implant positions in anterior versus posterior, maxilla versus mandible

Area	Entrance Deviation (mm)	*P* * *P* **	Apical Deviation (mm)	*P* * *P* **	Depth Deviation (mm)	*P* * *P* **	Angular Deviation (Degrees)	*P* * *P* **
Anterior (*N*=58)	0.50 ±0.41	**.041**	0.74 ±0.41	.244	0.42 ±0.55	.255	1.90 ±1.52	.573
Posterior (*N*=58)	0.37 ±0.25	.284	0.67 ±0.32	>.999	0.29 ±0.49	>.999	1.83 ±1.67	>.999
Maxilla (*N*=82)	0.44 ±0.37	.764	0.71 ±0.40	.669	0.42 ±0.53	**.025**	1.85 ±1.59	.904
Mandible (*N*=34)	0.42 ±0.25	>.999	0.69 ±0.26	>.999	0.19 ±0.47	.198	1.91 ±1.62	>.999

* Analysis carried out using mixed-effect model.
** Analysis carried out using Holm-Bonferroni Method.
Bold values indicate statistically significant differences between groups (*P*<.05).

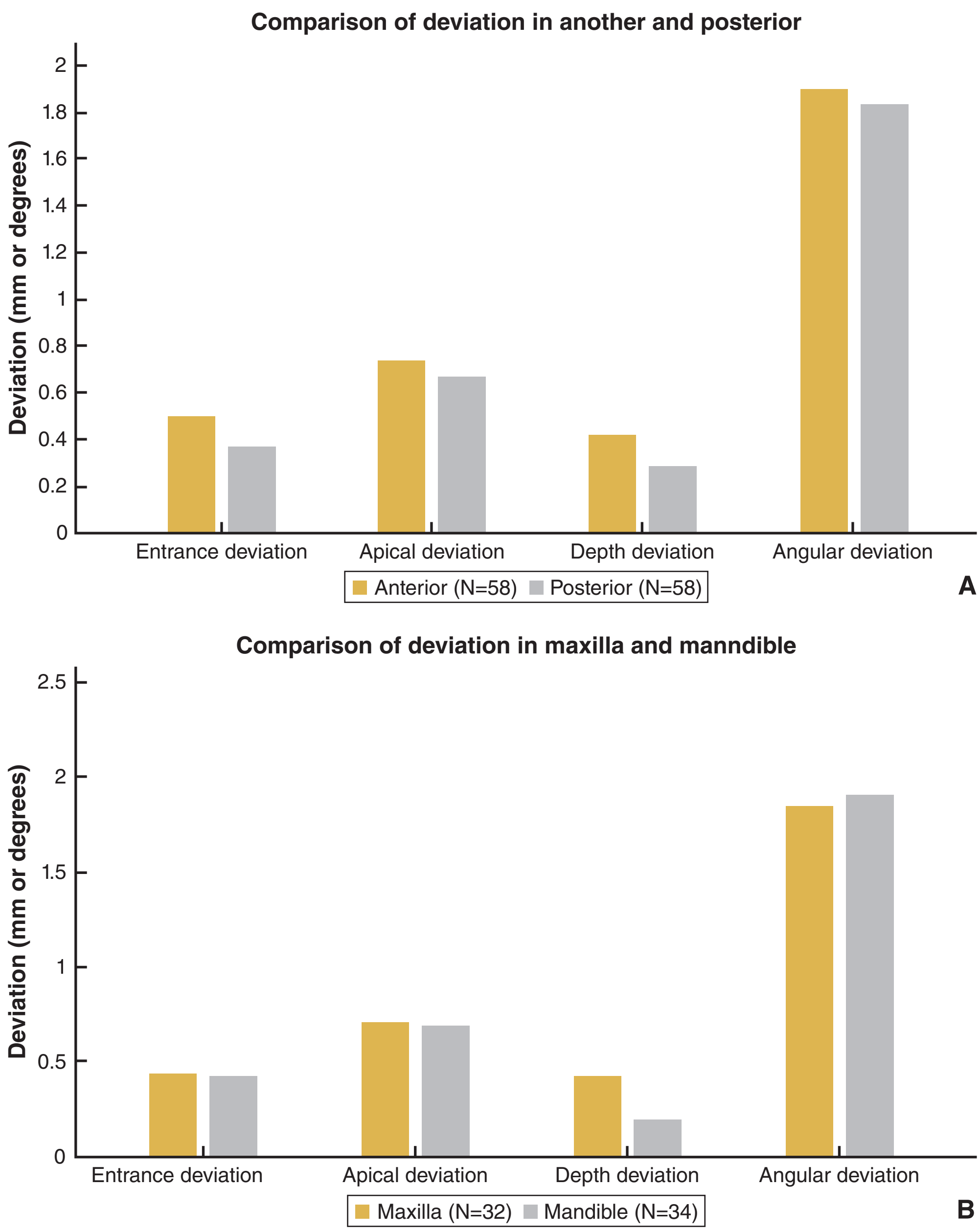

Figure 6. Difference between 4 areas of entrance, apex, angle, and depth. A. Between anterior and posterior groups. B, Between maxilla and mandible groups.

Table 3. Mean ±standard deviation values for direction of implant deviation in entrance and apex, between planned and actual implant positions

Area	Entrance Deviation (mm)	*P*	Apical Deviation (mm)	*P*
Anterior (*N*=58)	MB (*N*=26): 0.57 ±0.087 ML (*N*=7): 0.27 ±0.056 DB (*N*=16): 0.51 ±0.102 DL (*N*=9): 0.44 ±0.143	.394**	MB (*N*=30): 0.79 ±0.076 ML (*N*=3): 0.42 ±0.109 DB (*N*=17): 0.74 ±0.100 DL (*N*=8): 0.69 ±0.154	.491*
Posterior (*N*=58)	MB (*N*=19): 0.39 ±0.054 ML (*N*=16): 0.33 ±0.077 DB (*N*=10): 0.38 ±0.059 DL (*N*=13): 0.39 ±0.77	.923*	MB (*N*=20): 0.75 ±0.063 ML (*N*=15): 0.55 ±0.067 DB (*N*=14): 0.78 ±0.088 DL (*N*=9): 0.51 ±0.144	.071*
Maxilla (*N*=82)	MB (*N*=34): 0.54 ±0.071 ML (*N*=12): 0.20 ±0.040 DB (*N*=20): 0.46 ±0.082 DL (*N*=16): 0.38 ±0.092	**.029****	MB (*N*=38): 0.79 ±0.063 ML (*N*=8): 0.36 ±0.071 DB (*N*=23): 0.78 ±0.081 DL (*N*=13): 0.60 ±0.135	**.029***
Mandible (*N*=34)	MB (*N*=11): 0.36 ±0.542 ML (*N*=11): 0.43 ±0.098 DB (*N*=7): 0.43 ±0.093 DL (*N*=5): 0.55 ±0.115	.594*	MB (*N*=12): 0.74 ±0.088 ML (*N*=10): 0.66 ±0.062 DB (*N*=7): 0.64 ±0.134 DL (*N*=5): 0.66 ±0.082	.845*

DB, distobuccal; DL, distolingual; MB, mesiobuccal; ML, mesiolingual.
* Statistical analysis conducted using ANOVA.
** Statistical analysis conducted using Kruskal-Wallis.
Bold values indicate statistically significant differences between groups (*P*<.05).

workflow, including intraoral scanning, 3D radiographic imaging, implant planning software programs, and 3D printing. In the current study, from the highest deviation to the lowest, the global apical, global entrance, and depth deviations between the actual and the planned implant positions in the anterior zone were 0.74 ±0.41 mm, 0.50 ±0.41 mm, and 0.42 ±0.55 mm, and in the posterior zone were 0.67 ±0.32 mm, 0.37 ±0.25 mm, and 0.29 ±0.49 mm on average. Also, the angular deviation in the anterior zone was 1.90 ±1.52 degrees, and, in the posterior zone, it was 1.83 ±1.67 degrees on average. In terms of deviation values for direction, implant deviations were most significant in the maxilla, with the largest in the MB direction and the smallest in the ML direction (*P*<.05). Deviations in the mandible, anterior, and posterior regions were smaller and not statistically significant (*P*>.05).

The null hypothesis that no significant difference in the accuracy of printed tooth-supported implant surgical guides would be found between the anterior and posterior zones was not rejected, as the differences were statistically similar. The null hypothesis that no significant difference would exist in the accuracy of printed tooth-supported implant surgical guides between the maxilla and mandible was also not rejected. No significant differences were found in angular, apical, depth, or coronal deviations between the 2 jaws. Derksen et al[16] reported that factors like jaw type, flap design, and implant diameter did not significantly influence the accuracy of tooth-supported drill guides. Similarly, Huang et al[13] reported no significant differences between the maxilla and mandible in entrance, apical, and angular deviations, except for a slightly greater depth deviation in the maxilla, which was likely because the surgeon used A torque wrench after guide removal. Moreover, a review by Zhou et al[12] found no significant difference in linear deviations between the 2 jaws, although some studies, such as those by Ozan et al[17] and Cristache et al,[18] have suggested that mandibular surgical guides exhibit higher accuracy. In addition, Vasak et al[19] reported lower deviations in the mandible compared with those in the maxilla, specifically in the mesiodistal direction. However, their study used a different template-guided implantation system and had a smaller sample size of 86 implants. Lin et al[20] also reported statistically significant differences in apical deviation between the maxilla and mandible, which may have been influenced by different study designs.

However, a few studies reported more accuracy in maxillary surgical guides. Cassetta et al[21] indicated lower deviation for maxillary implant placement, but only in the mesiodistal direction. The type of surgical guide used in this study was mucosa-supported, which might explain the difference in results compared with those of the current study. Similarly, Cunha et al[22] reported greater angular, central, and coronal deviations in mandibular implants. The authors attributed their findings to reduced guide stability over the mandible due to limited contact area with the guide. Their study involved completely edentulous patients using complete dentures as surgical guides, which may explain the differences with the present study.

Based on the accuracy outcomes in the current evaluation, implant deviations ranked as follows: apical deviation was highest, likely because of bone density variations and anatomic constraints; entrance deviation was moderate, influenced by drill angulation and guide stability; and depth deviation was lowest, possibly because, as long as the guide remains stable, depth accuracy can often be achieved with minimal deviation. The inaccuracies in depth deviations resulted in implants being placed deeper than intended. Surgeons may deliberately place implants deeper to ensure secure anchorage within the bone. Ngamprasertkit et al[24] suggested that limited drilling length and surrounding reference points, such as the cementoenamel junction (CEJ) level of adjacent teeth or bone level at the surgical site, could be used as reference points for the implant insertion stop. Hence, determining and predicting depth is often precise. These findings were consistent with those of several studies. Huang et al[13] reported that the mean deviations for apical, coronal, depth, and angular positions in the anterior zone were 1.13 ±0.39 mm, 0.86 ±0.33 mm, 0.41 ±0.66 mm, and 3.32 ±1.65 degrees, respectively. According to Feng et al,[14] the mean global entrance and apical deviations in sCAIS for immediate implant placement were 0.99 ±0.63 mm and 1.50 ±0.75 mm, respectively, with an angular deviation of 3.07 ±2.18 degrees.

While the exact values may vary between studies, the relative order of deviations remains consistent. In vitro and cadaveric studies have tended to report higher accuracy associated with better visibility, while clinical situations may reduce accuracy because of patient-related factors. Variations also result from the lack of standardized evaluation methods, with some studies measuring global distance and others focusing on horizontal deviations. Previous systematic reviews by Shi et al[25] and Tahmaseb et al[4] have reported mean linear deviations below 2 mm and angular deviations within 5 to 8 degrees. In most clinical situations, the accuracy of sCAIS falls within an acceptable range, with a safety margin of at least 2 mm being necessary. The measured deviations in the current study were within commonly accepted clinical limits for guided implant placement (<2 mm safety margin and angular errors below commonly cited limits), supporting the clinical safety of the printed, tooth-supported guides used. Moreover, a stereolithography apparatus (SLA) 3D printer was used for surgical guide fabrication. Previous studies[8,9] have reported that SLA, digital light processing (DLP), and photopolymer jetting (PolyJet) technologies provide clinically acceptable accuracy and better guide seating than other methods.

Limitations of the study included that factors influencing guided implant accuracy, including alternative printing technologies, manufacturing parameters, different guide designs, and patient-related variables, were not evaluated. These unassessed elements highlight the need for future research to investigate their impact so that more comprehensive guidelines for predictable clinical outcomes can be established.

CONCLUSIONS

Based on the findings of this prospective observational clinical study, the following conclusions were drawn:

1. No significant difference in the accuracy of printed tooth-supported implant surgical guides was found between the anterior and posterior areas.
2. No significant difference in accuracy was found between the maxilla and mandible.
3. The maxilla exhibited the greatest deviation in the MB direction and the smallest in the ML direction, whereas other regions showed no significant differences.

PATIENT CONSENT

Informed consent was obtained from all participants and/or their legal guardian(s) for participation in the study. All methods were carried out in accordance with the Declaration of Helsinki.

REFERENCES

1. Panchal N, Mahmood L, Retana A, Emery R. Dynamic navigation for dental implant surgery. *Oral Maxillofac Surg Clin North Am*. 2019;31:539–547.
2. Yadav MK, Verma UP, Parikh H, Dixit M. Minimally invasive transgingival implant therapy: A literature review. *Natl J Maxillofac Surg*. 2018;9:117–122.
3. Laverty D, Buglass J, Patel A. Flapless dental implant surgery and use of cone beam computer tomography guided surgery. *Br Dent J*. 2018;224:591–602.
4. Tahmaseb A, Wu V, Wismeijer D, et al. The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clin Oral Implants Res*. 2018;29:416–435.
5. Al Yafi F, Camenisch B, Al-Sabbagh M. Is digital guided implant surgery accurate and reliable? *Dent Clin North Am*. 2019;63:381–397.
6. Tallarico M, Park C-J, Lumbau AI, et al. Customized 3D-printed titanium mesh developed to regenerate a complex bone defect in the aesthetic zone: A case report approached with a fully digital workflow. *Materials*. 2020;13:3874.
7. Ganz SD. Three-dimensional imaging and guided surgery for dental implants. *Dent Clin North Am*. 2015;59:265–290.
8. Kim T, Lee S, Kim GB, et al. Accuracy of a simplified 3D-printed implant surgical guide. *J Prosthet Dent*. 2020;124:195–201.e2.
9. Yeager B, Çakmak G, Zheng F, et al. Error analysis of stages involved in CBCT-guided implant placement with surgical guides when different printing technologies are used. *J Prosthet Dent*. 2024;132:995–1004.
10. Pozzi A, Polizzi G, Moy PK. Guided surgery with tooth-supported templates for single missing teeth: A critical review. *Eur J Oral Implantol*. 2016;9:S135–S153.
11. El Kholy K, Lazarin R, Janner SF, et al. Influence of surgical guide support and implant site location on accuracy of static Computer-Assisted Implant Surgery. *Clin Oral Implants Res*. 2019;30:1067–1075.
12. Zhou W, Liu Z, Song L, et al. Clinical factors affecting the accuracy of guided implant surgery—A systematic review and meta-analysis. *J Evid Based Dent Pract*. 2018;18:28–40.
13. Huang L, Zhang X, Mo A. A retrospective study on the transferring accuracy of a fully guided digital template in the Anterior Zone. *Materials*. 2021;14:4631.
14. Feng Y, Su Z, Mo A, Yang X. Comparison of the accuracy of immediate implant placement using static and dynamic computer-assisted implant system in the esthetic zone of the maxilla: A prospective study. *Int J Implant Dent*. 2022;8:65.
15. Chen Z, Li J, Sinjab K, et al. Accuracy of flapless immediate implant placement in anterior maxilla using computer-assisted versus freehand surgery: A cadaver study. *Clin Oral Implants Res*. 2018;29:1186–1194.
16. Derksen W, Wismeijer D, Flügge T, et al. The accuracy of computer-guided implant surgery with tooth-supported, digitally designed drill guides based on CBCT and intraoral scanning. A prospective cohort study. *Clin Oral Implants Res*. 2019;30:1005–1015.
17. Ozan O, Turkyilmaz I, Ersoy AE, et al. Clinical accuracy of 3 different types of computed tomography-derived stereolithographic surgical guides in implant placement. *J Oral Maxillofac Surg*. 2009;67:394–401.
18. Cristache CM, Gurbanescu S. Accuracy evaluation of a stereolithographic surgical template for dental implant insertion using 3D superimposition protocol. *Int J Dent*. 2017;2017:4292081.
19. Vasak C, Watzak G, Gahleitner A, et al. Computed tomography-based evaluation of template (NobelGuide)-guided implant positions: A prospective radiological study. *Clin Oral Implants Res*. 2011;22:1157–1163.
20. Lin YK, Yau HT, Wang IC, et al. A novel dental implant guided surgery based on integration of surgical template and augmented reality. *Clin Implant Dent Relat Res*. 2015;17:543–553.
21. Cassetta M, Giansanti M, Di Mambro A, Stefanelli LV. Accuracy of positioning of implants inserted using a mucosa-supported stereolithographic surgical guide in the edentulous maxilla and mandible. *Int J Oral Maxillofac Implants*. 2014;29:1071–1078.
22. Cunha RM, Souza F, Hadad H, et al. Accuracy evaluation of computer-guided implant surgery associated with prototyped surgical guides. *J Prosthet Dent*. 2021;125:266–272.

23. International Organization for Standardization. Accuracy (Trueness and Precision) of Measurement Methods and Results—Part 1: General Principles and Definitions (ISO 5725-1:2023). ISO; 2023.
24. Ngamprasertkit C, Aunmeungthong W, Khongkhunthian P. The implant position accuracy between using only surgical drill guide and surgical drill guide with implant guide in fully digital workflow: A randomized clinical study. *Oral Maxillofac Surg*. 2022;26:229–237.
25. Shi Y, Wang J, Ma C, et al. A systematic review of the accuracy of digital surgical guides for dental implantation. *Int J Implant Dent*. 2023;9:38.

Corresponding author:
Dr Zahra Khayami
Department of Restorative Dentistry
School of Dentistry
Ahvaz Jundishapur University of Medical Sciences
Ahvaz 6135715794
IRAN
Email: Zahrakhayami95@gmail.com

Acknowledgments
The authors thank all the clinical and technical staff involved in this study for their dedicated support and contributions. The authors also thank Seyed Mohammad Amin Alavi for his invaluable assistance with the study's statistical analysis.

CRediT authorship contribution statement
Alireza Rezaei: Conceptualization, Methodology, Software. **Farnoush Fotovat:** Supervision. **Ali Heidari:** Project administration. **Zahra Khayami:** Writing-original draft preparation, Data Curation, Visualization. **Zahra Khalafi:** Investigation, Resources. **Loghman Rezaei-soufi:** Validation, Writing - Review and Editing.

https://doi.org/10.1016/j.prosdent.2025.12.026