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Original Article

Impact of bone surface inclination on the precision of static fully guided implant surgery: A quantitative analysis

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KEYWORDS
Bone surface inclination;
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Abstract *Background/purpose:* Although static fully guided systems improve the accuracy of implant placement, most studies have focused on flat bone surfaces, with limited exploration of the effects of sloped bone surface. In this study, we aimed to evaluate the effects of bone surface inclination on the accuracy of static fully guided implant surgery.
Materials and methods: Three 3D-printed maxillary models with a missing upper right lateral incisor were fabricated and each accommodated artificial bone blocks (Sawbones®). Bone blocks were grouped according to the buccal surface inclination (0°, 30°, and 60°; n = 10 per group). A static fully guided surgical system was designed using cone beam computed tomography and model scan data, and implants (Nobel Parallel Conical Connection RP, 4.3 mm × 13 mm) were placed by a single operator. The post-placement accuracy was assessed by mapping the scanned implant data with the surgical plan in Geomagic Control X. Deviations in the entry point, apex, vertical and horizontal positions, as well as angular deviation, were measured. Statistical analysis was performed using one-way ANOVA with Bonferroni post hoc test ($P < 0.05$).
Results: Significant differences were observed in the entry point, apex, angular, and vertical deviations across the inclination groups; however, no significant difference was found in the horizontal deviations. Of the 30 implants, 23 deviated toward the buccal side.
Conclusion: Bone surface inclination significantly affects the accuracy of static, fully guided implant surgery. Preoperative planning and guide design should consider these effects in order to optimize implant placement outcomes.

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Introduction

Ideal positioning of dental implants is a crucial determinant of implant success. Factors, including inter-implant distance, dimensions between implants and natural teeth, depth, and buccal bone thickness, must fall within appropriate ranges. A key factor in implant success is the achievement of accurate implant positioning, rather than relying solely on surgical techniques.[1] Proper implant placement ensures the stability of both hard and soft tissues, allowing prostheses to achieve optimal occlusal balance and load distribution.[2] Furthermore, well-designed prostheses maintain aesthetics, enable the fabrication of screw-retained prostheses for convenient maintenance, and reduce the risk of peri-implantitis by minimizing bacterial accumulation.[3]

Improper implant positioning can damage vital anatomical structures and compromise both aesthetics and biomechanics. For example, buccal-side screw access holes or exposed implant threads detract from appearance. To address this, some clinicians use cement-retained crowns, but residual cement in the gingival sulcus increase the risk of peri-implantitis.[4] Biologically, suboptimal prosthetic designs hinder hygiene and promote plaque accumulation, elevating failure risk. Mechanically, implants misaligned with occlusal force axes endure lateral stress, which may cause screw loosening or fractures.[5,6] Implant positioning is particularly critical in the anterior region, as suboptimal placement can severely compromise aesthetics.[7] Immediate implant placement (IIP) is frequently used in this region to reduce treatment time and allow the placement of temporary prostheses, while preserving aesthetics and social confidence. However, in IIP, the drill must penetrate the buccal slope of the extraction socket, which often lacks a stable surface. This instability increases the likelihood of drill slippage and implant positioning errors.[8]

Historically, freehand implant surgery has relied heavily on the surgeon's extensive experience to minimize positional deviations. Recent advances in computer-assisted implant surgery (CAIS) have enabled the integration of cone beam computed tomography (CBCT)-derived data with intraoral and model scan data. This allows for the preoperative planning of 3D implant positions customized to the patient's specific anatomical conditions.[9—12] By combining thorough preoperative planning with the CAIS, the accuracy of implant placement can be significantly improved, ensuring closer alignment between the actual implant position and the preoperative plan. This approach enhances the long-term survival and success rates of implants and prosthetic restorations.

Mean deviations of 1.04—1.45 mm at the implant entry point, 1.38—2.99 mm at the apex, and angular deviations of approximately 4° with static CAIS (s-CAIS) have been reported.[13,14] Similarly, Kraft et al.[15] investigated s-CAIS outcomes in anterior IIP cases by comparing fully and partially guided surgeries and found that while entry point deviations were comparable (1.34 ± 0.99 mm vs. 1.26 ± 0.5 mm), fully guided surgeries exhibited greater apical (2.50 ± 1.67 mm vs. 1.97 ± 1.04 mm) and angular deviations (5.36 ± 4.53° vs. 3.60 ± 2.84°). These results suggest that the accuracy of the s-CAIS for irregular extraction sockets may be inferior to that reported by Tahmaseb and Jung.[13]

Wang et al.[16] compared static and dynamic CAIS on extraction sockets and healed bones using an in vitro model. Their results showed that dynamic CAIS achieved superior accuracy in entry point deviation (0.60 ± 0.29 mm vs. 1.24 ± 0.26 mm), apical deviation (0.78 ± 0.33 mm vs. 1.69 ± 0.34 mm), and angular deviation (2.47 ± 1.09° vs. 3.44 ± 1.06°). Furthermore, the dynamic CAIS demonstrated consistent performance across different bone surfaces, unlike the s-CAIS, which was more affected by surface irregularities. The primary limitation of s-CAIS is its inability to modify implant positions intraoperatively, unlike dynamic CAIS, which allows real-time adjustments.[12] Both Kraft and Wang's studies highlighted the greater impact of bone surface morphology on s-CAIS accuracy than on dynamic CAIS. However, most CAIS studies that have been conducted to date have focused on flat bone surfaces and neglected the potential effects of bone surface inclination. For example, in IIP, the angle of the extraction socket may differ from the planned implant position, necessitating specific strategies to achieve optimal outcomes.[17] The angle between the drill and the bone surface significantly affects implant placement accuracy. Clinically, uneven bone surfaces are common in scenarios such as uneven alveolar resorption, tilted implants in the all-on-four concept, and IIP procedures. However, few studies have explored the accuracy of s-CAIS for inclined bone surfaces.

In this study, we aimed to evaluate the accuracy of s-CAIS for implant placement on bone surfaces with varying inclinations and to analyze deviations to determine whether bone surface inclination affects precision. The null hypothesis was that implant accuracy using static guides is not influenced by the degree of bone surface inclination.

Materials and methods

This study involved implant placement by a single operator on bone surfaces at three different inclination angles using static surgical guides. After implant placement, the scan bodies were attached, and the implants were scanned using a lab scanner. Deviations between the preoperative design and actual implant positions were calculated using verification software. Statistical analyses were conducted to evaluate the effect of bone surface inclination on implant accuracy.

Preoperative preparations

Standard model fabrication

A 3Shape E3 lab scanner (3shape, Copenhagen, Denmark) was used to scan a simulated patient model, generating an STL file. Using computer-aided designing software (Meshmixer, Autodesk, Inc., San Francisco, CA, USA), a recess measuring 8.3 mm (L) × 8.3 mm (W) × 25 mm (H) was designed at the bone block position. The standard models were 3D printed with a high-temperature-resistant resin (TR250LV, Phrozen Tech Co. Ltd., Hsinchu City, Taiwan) using a Phrozen Sonic XL 4K 3D printer (Phrozen Tech Co. Ltd.) (Fig. 1). Three experimental models were fabricated and labeled Models A, B, and C.

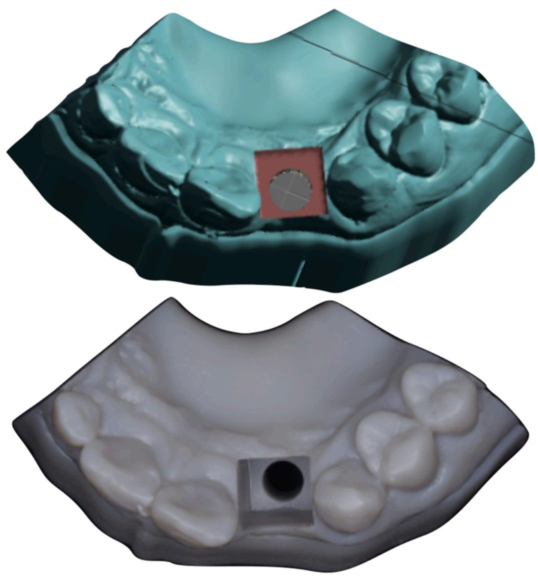

Figure 1 Standard model. (a) designed standard model; (b) 3D-printed standard model.

Preparation of simulated bone blocks

Polyurethane biomechanical test blocks (Sawbone®, Pacific Research Laboratories, Inc., Vashon, WA, USA), simulating human trabecular bone, were selected. These blocks had a density of 30 pcf, closely resembling the Misch classification of the D1 bone. The blocks were processed using a CNC module (Snapmaker 2.0 A350T, Shenzhen, China) equipped with a 3.0 mm drill bit. The cutting paths were designed using computer-aided design software (Meshmixer, Autodesk, Inc.) and transferred to Snapmaker for execution. The blocks were cut to dimensions of 8 mm (L) × 8 mm (W) × 25 mm (H) (Fig. 2). The bone surfaces were shaped at three inclination angles: 0°, 30°, and 60° (Fig. 3). Each group contained 10 blocks, for a total of 30 simulated bone blocks.

Experimental model and bone block grouping

The 30 simulated bone blocks were evenly distributed among the three models. Each experimental model was designed to allow the easy replacement of bone blocks after each procedure.

Implant position design

Implant positions were planned using Design Studio Implant Studio software (3shape) based on CBCT and intraoral scan data. Implants were planned at tooth 12 using the Nobel Parallel Conical Connection RP 4.3 × 13 mm implants (Nobel Biocare Services AG, Kloten, Switzerland) (Fig. 4).

Fabrication of fully guided static surgical guides

Surgical guides were designed to span teeth 14–21, ensuring cross-arch tooth support. The guides were

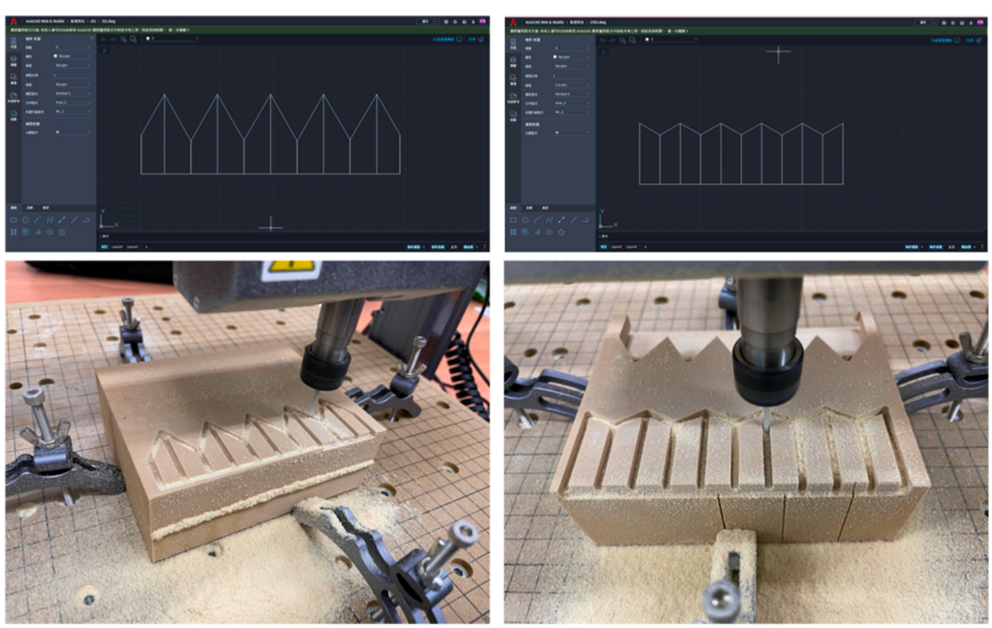

Figure 2 Design and production of test bone blocks: (a) 60° bone block design, (b) 30° bone block design, (c) 60° bone block production, and (d) 30° bone block production.

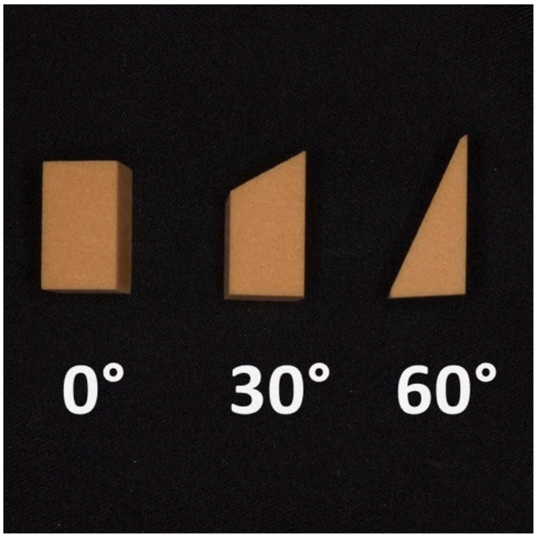

Figure 3 Test bone blocks at 0°, 30°, and 60° inclination.

fabricated with DD guide material (Enlighten Materials Co., Ltd., Taipei City, Taiwan) and 3D printed using a Phrozen Sonic XL 4K printer. Nobel Biocare RP-guided metal sleeves were inserted and fixed using an adhesive (Fig. 4).

Preparation of preoperative models

Prepared bone blocks were embedded into the recesses of standard models using dental gypsum (Yoshino Gypsum Co., Ltd., Tokyo, Japan). The static surgical guide was securely positioned on the model and proper alignment was confirmed through the guide windows (Fig. 4).

Implant placement procedure

Equipment and protocols

Implant placement was performed using an NSK Surgic XT Plus handpiece (NSK Ltd., Tokyo, Japan) paired with a Mont Blanc 20:1 Push Button Dental Implant Handpiece. The Nobel Biocare-Guided Surgery Kit was used following the Dense Bone Type I (30 pcf) surgical protocol provided by the manufacturer.

Postoperative analysis — Non-radiographic method

Scanning the implants. After implant placement, scan bodies (Elos Accurate IO Nobel CC RP Single Abutment; Elos Medtech AB, Göteborg, Sweden) were attached. Implants were scanned using a E3 lab scanner (3shape), and STL files were generated (Fig. 5).

Accuracy calculation. Implant accuracy was analyzed using Geomagic Control X 2020.1 software (3D Systems Corporation, Rock Hill, SC, USA). The preoperative design files were aligned with the postoperative STL scans to calculate the deviations (Fig. 5). The center of the sleeve plane of the surgical guide served as the reference point. The implant entry point was located 9 mm along the axis from this reference point, with the apex positioned 13 mm away from it. The implant axis was calculated

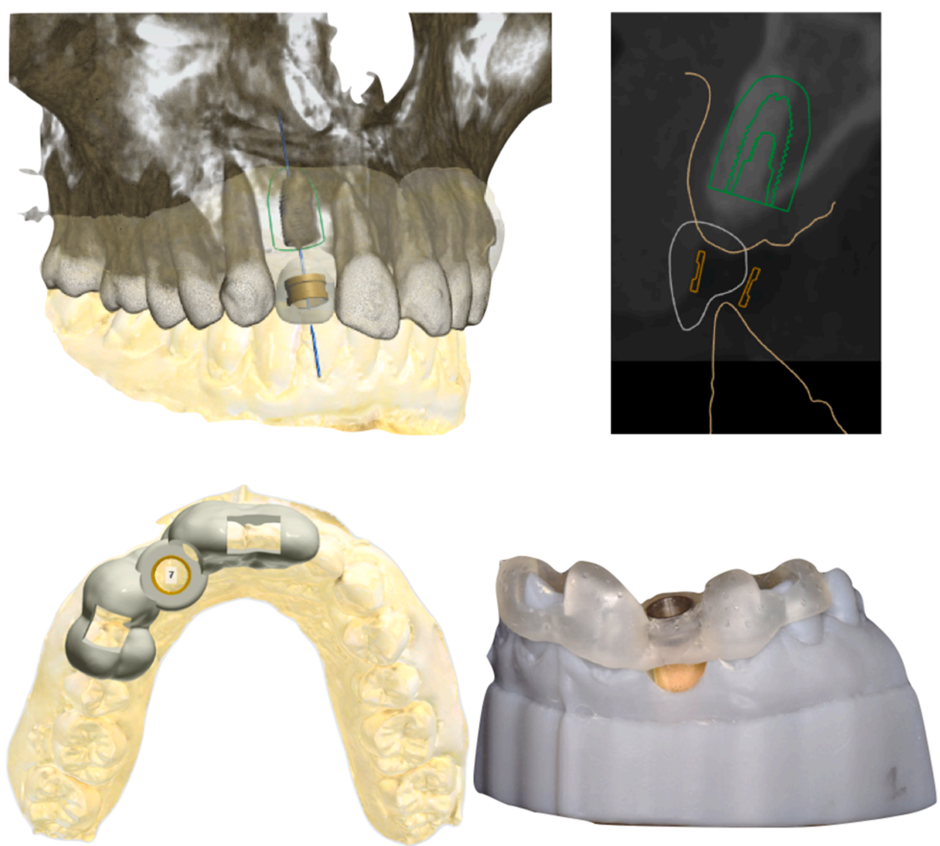

Figure 4 Implant planning and surgical guide: (a) implant planning at tooth 12; (b) sectional view of implant planning; (c) surgical guide design; and (d) surgical guide positioned on the standard model.

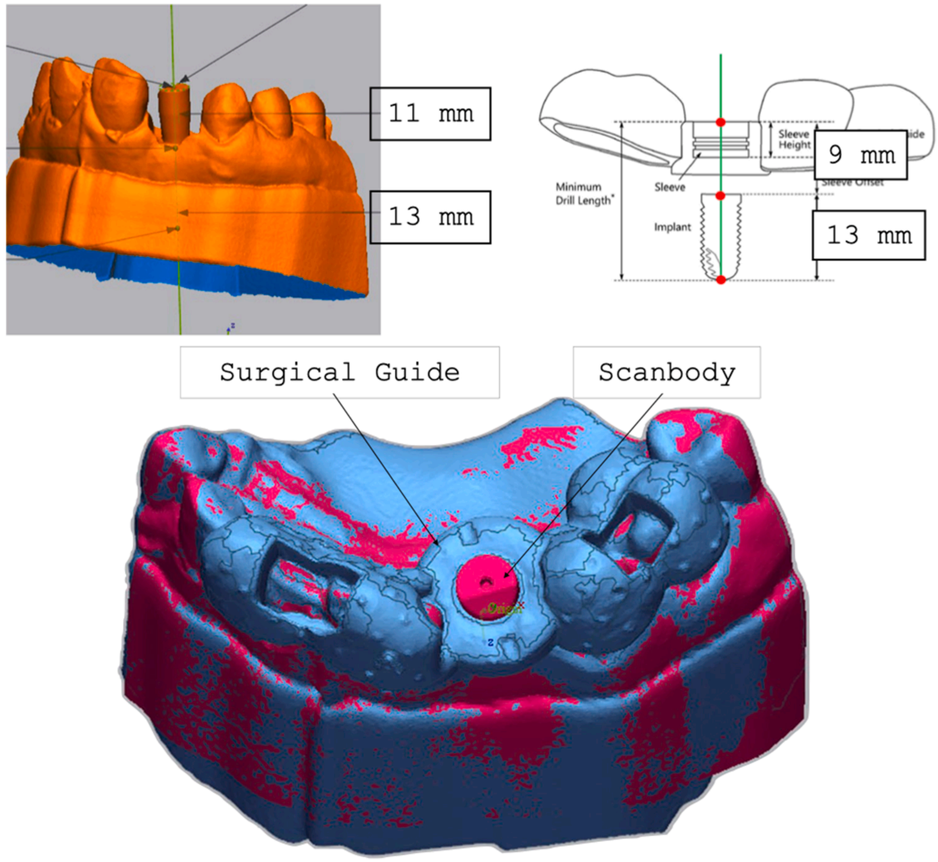

Figure 5 Postoperative evaluation method without radiation exposure. (a) determination of the actual implant position using scan body data from postoperative scans; (b) determination of the planned implant position using surgical guide data from preoperative planning; and (c) alignment of the surgical guide and scan body to calculate accuracy.

based on these points (Fig. 5). The center of the top plane of the scanned body served as the reference. The implant entry point and apex were determined to be similar to those in the design file analysis (Fig. 5).

The following five accuracy parameters were calculated: (a) deviation at the implant entry point; (b) deviation at the implant apex; (c) angular deviation of the implant axis; (d) deviation in the vertical implant position; and (e) deviation in the horizontal implant position (Fig. 6).

Statistical analysis

Raw data were organized using Microsoft Excel (V14.1, Microsoft Corp., Redmond, WA, USA) and analyzed using SPSS (V19.0, IBM Corp., Armonk, NY, USA). One-way repeated-measures ANOVA was performed to identify significant differences among the three inclination groups. Bonferroni tests were applied when significant differences were detected to identify specific group variations. A P-value <0.05 was considered statistically significant.

Results

Accuracy measurements by inclination angles

The accuracy of implant placement was analyzed for different inclination angles, and the results are presented as mean ± standard deviation. The detailed data are summarized in Table 1.

One-way repeated-measures ANOVA

A one-way repeated-measures ANOVA was performed to assess the effect of different inclination angles on the five accuracy parameters (Table 2). No significant differences were found in deviation in the horizontal position.

Post-hoc analysis

Bonferroni post-hoc tests were conducted to identify specific differences between the groups (Table 3). For deviation at apex, significant differences were observed between the 0° and 30° groups and the 0° and 60° groups. For angular deviation, significant differences were found between the 0° and 60° groups. For deviation in vertical position, significant differences were found between the 0° and 60° groups and 30° and 60° groups.

Implant deviation distribution

The deviations were categorized into buccal, palatal, mesial, and distal directions. The distribution of the 30 simulated bone blocks is shown in Fig. 7 (buccal deviation: 23 cases; palatal deviation: 7 cases; mesial deviation: 16

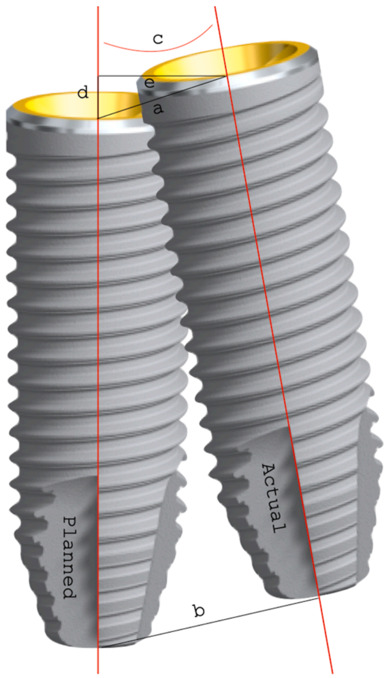

Figure 6 Definition of accuracy parameters: (a) deviation at the implant entry point; (b) deviation at the implant apex; (c) angular deviation of the implant axis; (d) deviation in vertical implant position; and (e) deviation in horizontal implant position.

cases; distal deviation: 14 cases). Details of the directional deviations are summarized in Table 3.

Statistical analysis of directional deviations

Buccal vs. palatal groups: Fisher's exact test revealed no significant difference ($P = 0.999$).

Mesial vs. distal groups: Fisher's exact test showed no significant difference ($P = 0.106$).

Proportional analysis of buccal deviations

As the buccal group showed significantly more deviations (23 cases) than the other groups, a one-sample proportion test was conducted. The results showed a significant difference ($P = 0.0031$).

Discussion

Some studies use multiple sequential guides paired with gradually enlarging drills, whereas others employ a single guide combined with drill sleeves of various sizes. Certain systems provide full guidance during both drilling and implant placement (fully guided), whereas others only guide the drilling phase, leaving implant placement unguided (partially guided). According to the International Team for Implantology Consensus Conference 2013, fully guided systems ensure greater precision and consistency during implant placement than alternative methods.[13,18,19]

Static surgical guides also vary in their support types, including tooth-supported, tissue-supported, bone-supported, and specialized supports, including miniscrews.[20] Tooth-supported guides offer superior accuracy compared with other support types.[21] In our study, tooth 12, which is an area with intact adjacent teeth, was selected as the implant site. A tooth-supported guide with extended coverage was used to enhance the stability.

Three experimental models and 30 static surgical guides were fabricated using the 3D printing technology, employing identical files, a single 3D printer (Phrozen Sonic XL 4 K), and uniform resin materials. The finished products were stored in dark bags to prevent the deformation caused by light exposure. The simulated bone blocks were precisely machined using CNC technology to ensure a uniform inclination angle and surface smoothness. The bone blocks were embedded in the recess of the standard model with gypsum to maintain consistent conditions across groups while closely simulating clinical scenarios. A single experienced right-handed implant surgeon performed the procedures, while strictly adhering to the Nobel Biocare-Guided Surgery protocol to minimize human variability.

In this study, D1-type bone blocks (30 pcf) were used to standardize experimental conditions and to better simulate cortical bone, where the influence of surface inclination is most critical during the initial drilling perforation. This approach ensured consistency and clinical relevance; however, the results may not fully represent implant behavior in lower-density bone (D2—D4). As the literature shows conflicting findings regarding the relationship between bone density and drill deviation,[22,23] future investigations including a broader range of bone densities are warranted to validate and expand upon the present results.

Traditionally, implant accuracy has been calculated using Co-DiagnostiX or Mimics software by overlaying pre- and postoperative CBCT scans to automatically measure deviations in implant positions.[24,25] However, to adhere to

Table 1 Accuracy at 0°, 30°, and 60° inclinations.

Mean	a (mm)	b (mm)	c (°)	d (mm)	e (mm)
0° group	1.23 ± 0.23	1.24 ± 0.24	1.59 ± 0.92	1.2 ± 0.23	0.29 ± 0.06
30° group	1.27 ± 0.32	1.85 ± 0.46	3.86 ± 1.68	1.16 ± 0.36	0.42 ± 0.20
60° group	0.98 ± 0.21	1.78 ± 0.43	6.13 ± 2.81	0.80 ± 0.30	0.49 ± 0.22

(a) deviation at the implant entry point; (b) deviation at the implant apex; (c) angular deviation of the implant axis; (d) deviation in the vertical implant position; (e) deviation in the horizontal implant position.

Table 2 One-way ANOVA (comparative analysis across inclination groups).

	Mean	Standard deviation	*P*-value
Outcome a			0.039[a]
0	1.23	0.23	
30	1.27	0.32	
60	0.98	0.21	
Outcome b			0.008[a]
0	1.24	0.24	
30	1.85	0.46	
60	1.78	0.43	
Outcome c			0.000[a]
0	1.59	0.92	
30	3.86	1.68	
60	6.13	2.81	
Outcome d			0.015[a]
0	1.2	0.23	
30	1.16	0.36	
60	0.8	0.3	
Outcome e			0.062
0	0.29	0.06	
30	0.42	0.2	
60	0.49	0.22	

(a) deviation at the implant entry point; (b) deviation at the implant apex; (c) angular deviation of the implant axis; (d) deviation in the vertical implant position; (e) deviation in the horizontal implant position.

[a] Statistically significant ($P < 0.05$).

the "as low as reasonably achievable" (ALARA) principle for radiation exposure, we utilized guide and scan body features to align preoperative plans with postoperative models, enabling accurate implant position calculations.[26] The planned and actual implant positions were determined using the respective features of the surgical guide and scan body, and all analyses were performed by the same operator to ensure consistency. Studies of implant accuracy mainly assessed deviation at the entry point, deviation at the apex, and angular deviation. The deviation at the entry point can be further divided into vertical and horizontal deviations.[26]

Literature reports average deviations for static guided implants as follows: entry point 1.25 ± 0.04 mm, apex 1.57 ± 0.05 mm, and angular deviation 4.1 ± 0.13°.[27] The deviations observed in the 0° group (entry, apex, and angular) were comparable to those reported in previous studies on flat bone surfaces using static fully guided surgery.[13,14] This alignment suggests that the present in vitro model successfully replicated clinical conditions. Minor differences in deviation values may be attributed to variations in guide support design, implant system, operator experience, or the method of accuracy assessment (optical scanning versus CBCT superimposition).

However, the 30° and 60° groups demonstrated larger deviations, highlighting the significant effect of bone surface inclination on implant accuracy. Consequently, the null hypothesis that the implant accuracy is unaffected by the bone surface inclination was rejected. Moreover, no significant differences were observed in the implant entry point deviations in the buccal, lingual, mesial, and distal directions, likely because of the limited sample size. The distribution of the implant entry point deviations (Fig. 7) revealed that the 0° group exhibited more concentrated deviations, whereas the 30° and 60° groups showed more dispersed distributions.

Clinically, in cases with buccal-inclined bone surfaces, deviations may exceed the generally accepted safety zones (2 mm linear, 4° angular).[13,14] In such situations, adjustments in the drilling protocol can help minimize slippage and positional errors. Practical strategies include flattening the inclined bone surface with a cutter before drilling, modifying the drill entry angulation to achieve a more stable initial penetration, and enhancing surgical template stability to reduce micromovement during osteotomy. These measures may improve implant placement accuracy on steeply inclined bone surfaces. Nevertheless, the metal sleeve of the static surgical guide effectively restricted the drill movement, ensuring that the overall deviations did not significantly deviate from the planned implant positions.

Further analysis indicated that buccal deviations occurred in 17 of 20 cases in the 30° and 60° groups, significantly outnumbering deviations in the other directions. A one-sample proportion test revealed a *P*-value of 0.0031, which indicated a statistically significant difference. These findings suggest that implant entry points tend to deviate buccally, which is consistent with the inclination of the bone surface, as drills are more likely to slide along the sloped surface.

Clinically, uneven bone surfaces, including excessively resorbed alveolar ridges or sloped extraction sockets, are frequently encountered.[28,29] Under such conditions, careful assessment of the bone surface and precise surgical guide design are essential for enhancing the accuracy and safety of implant procedures.

This study has several limitations. Besides the relatively small sample size, the in vitro models did not include soft-tissue simulation, which may influence guided template stability and intraoperative handling. In addition, only one implant system and a static fully guided approach were tested, limiting the generalizability of the findings. Clinical conditions such as bleeding, restricted intraoral space, and patient-related variables were also not represented in the experimental setup. Future studies should explore the performance of different implant systems, evaluate the impact of soft-tissue simulation, and compare static guides with dynamic navigation approaches. Moreover, investigations including multiple operators would be valuable to assess the influence of surgical experience and technique on implant accuracy. Finally, systematic evaluations of modified drilling protocols on inclined bone surfaces are warranted to optimize clinical outcomes.

In conclusion, the accuracy of implant placement using static, fully guided surgical systems is influenced by the degree of bone surface inclination. Significant differences in the entry point and apical, angular, and vertical deviations were observed across groups with varying bone surface inclinations, which suggested that surface geometry affects implant accuracy. Bone surfaces that slope buccally cause implants to deviate toward the buccal side. Preoperative planning should account for bone surface inclination to improve the accuracy of implant placement.

Table 3 Post-hoc multiple comparisons using Bonferroni test to evaluate intergroup differences.

Outcome	(I) Degree	(J) Degree	MD (I-J)	Standard error	Significance	95 % Confidence interval	
						Lower bound	Upper bound
a	0	30	−0.045	0.1212951	1.000	−0.354601	0.264601
		60	0.2595	0.1212951	0.125	−0.502101	0.569101
	30	0	0.045	0.1212951	1.000	−0.264601	0.354601
		60	0.3045	0.1212951	0.055	−0.005101	0.614101
	60	0	−0.2595	0.1212951	0.125	−0.569101	0.050101
		0	−0.3045	0.1212951	0.055	−0.614101	0.050101
b	0	0	−0.5666	0.1841806	0.014[a]	−1.036713	−0.096487
		0	−0.5133	0.1841806	0.029[a]	−0.983413	−0.043187
	30	0	0.5666	0.1841806	0.014[a]	0.096487	1.036713
		0	0.0533	0.1841806	1.000	−0.416813	0.523413
	60	0	0.5133	0.1841806	0.029[a]	0.043187	0.983413
		0	−0.0533	0.1841806	1.000	−0.523413	0.416813
c	0	0	−2.114	0.925105	0.091	−4.475293	0.247293
		0	−4.395	0.925105	0.000[a]	−6.756293	−2.033707
	30	0	2.114	0.925105	0.091	−0.247293	4.475293
		0	−2.281	0.925105	0.061	−4.642293	0.080293
	60	0	4.395	0.925105	0.000[a]	2.033707	6.756293
		0	2.281	0.925105	0.061	−0.080293	4.642293
d	0	0	0.0293	0.1410336	1.000	−0.330682	0.389282
		0	0.3981	0.1410336	0.026[a]	0.038118	0.758082
	30	0	−0.0293	0.1410336	1.000	−0.389282	0.330682
		0	0.3688	0.1410336	0.043[a]	0.009919	0.728782
	60	0	−0.3981	0.1410336	0.026[a]	−0.758082	−0.038118
		0	−0.3688	0.1410336	0.043[a]	−0.728782	−0.008818
e	0	0	−0.168	0.0821248	0.152	−0.37762	0.04162
		0	−0.1843	0.0821248	0.100	−0.39392	0.02532
	30	0	0.168	0.0821248	0.152	−0.04162	0.37762
		0	−0.163	0.0821248	1.000	−0.22592	0.19332
	60	0	0.1843	0.0821248	0.100	−0.02532	0.39392
		0	0.0163	0.0821248	1.000	−0.19332	0.22592

(a) deviation at the implant entry point; (b) deviation at the implant apex; (c) angular deviation of the implant axis; (d) deviation in the vertical implant position; (e) deviation in the horizontal implant position.
(I), (J): groups being compared (0°, 30°, 60° inclination).
MD (I–J): mean difference between groups I and J.
[a] Statistically significant ($P < 0.05$).

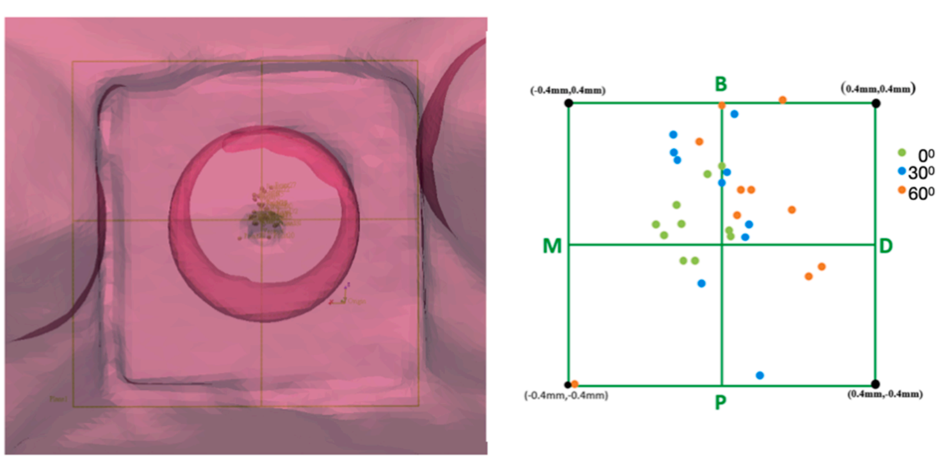

Figure 7 Distribution of implant entry points in buccal, lingual, mesial, and distal directions. (a) actual distribution map. (b) coordinate-based distribution map.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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