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Original Article

Accuracy Assessment of Static Guided Implant Surgery: A Comparison between Two Digital Planning Platforms

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ABSTRACT

To compare the divergence between the preoperatively designed and the clinically achieved positions of a single posterior implant with the same length, employing two commonly utilized static implant planning software applications within a tooth-supported, partially guided surgical framework. A total of 75 implant placement instances were reviewed in this retrospective analysis. The preoperative design was performed using the GuideMia Implant System in 40 cases and the 3Shape Implant Studio in 35 cases. The actual implant location captured on postoperative cone-beam computed tomography was fused with the virtual treatment plan. For both cohorts, coronal, apical, and angular discrepancies in the 3D spatial orientation were quantified via an auxiliary evaluation software tool. Six variables with the potential to affect precision were individually assessed: the arch, the placement site, the implant brand, the absence of distal abutment teeth, and the implant dimensions (length and diameter). To trace the origins of the observed discrepancies, linear regression models were developed. The comparison of the two implant planning software solutions revealed no statistically significant difference, regardless of implant length (8, 10, or 12 mm, $P > 0.05$). Conversely, notable differences were recorded for the entry point ($P = 0.003$), the apical termination($P = 0.005$), and the angular orientation ($P = 0.002$) when contrasting free-end scenarios with bounded saddle scenarios. The planning software applications demonstrated comparable precision in implant placement for identical implant lengths. Nonetheless, the positioning of an implant at the distal extension of a posterior single-tooth edentulous space significantly influences overall accuracy.

Keywords: 3Shape implant studio, Computer-aided implant surgery, Digital workflow, GuideMia, Implant-planning software

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Introduction

The practice of computer-guided implant surgery integrates interdisciplinary research on computer-aided design and manufacturing [CAD/CAM] technology, radiographic imaging methodology, and three-dimensional (3D) printing, all directed toward achieving “prosthetic-driven” precision in implant placement [1, 2]. Implant planning software is a digital platform that provides clinicians with registered digital images and manipulable 3D structural data to execute the required preoperative blueprint [3, 4]. This dataset is then used to fabricate the surgical guide, aiding clinicians in precisely and safely placing implants while avoiding iatrogenic injury to adjacent dental roots, the inferior alveolar nerve, or the maxillary sinus cavities. Accordingly, software demonstrating high accuracy provides measurements that are both more

dependable and more precise, thereby enabling optimal implant positioning that considers neighboring anatomical landmarks and the targeted prosthetic reconstruction [5]. The importance of this accuracy is heightened in situations of multiple tooth loss or complete edentulism, where marked angular implant discrepancy poses substantial challenges for the ensuing prosthetic phase and may precipitate biomechanical complications [6]. A body of clinical evidence confirms that computer-aided implant procedures minimize patient morbidity and achieve positioning more precise than that attainable with traditional freehand techniques [7–9]. Guided implant surgery systems are divided into two modalities: static [template-assisted] and dynamic navigation. At present, static methodologies enjoy wider adoption, a preference attributable to their lower financial outlay and spatial footprint compared with dynamic navigation setups [10–12]. These static methodologies can be subdivided into partially guided protocols [involving only guided osteotomy] and fully guided protocols [encompassing both guided osteotomy and guided fixture delivery]. Partially guided surgical stents afford the surgeon the latitude to assess and adjust the final drilling trajectory, insertion angle, and vertical implant depth, enabling real-time corrections for any positional drift during the operation. It should be noted, however, that partially guided approaches may exhibit greater dispersion in implant deviation than their fully guided counterparts, a phenomenon particularly evident in distal extension regions and angular placement parameters [4, 13].

The year 1998 marked the commercial debut of the first computer-aided dental implant planning platform, SimPlant, developed by the Colombia Technology Company, which made preoperative planning and design feasible for guided implant surgery [14]. In the years that followed, a variety of companies introduced their own planning solutions, among them SimPlantTM (Materialize, Leuven, Belgium), Nobel GuideTM (Nobel Biocare, Gothenburg, Sweden), coDiagnostiX (Dental Wings GmbH), GuideMia Implant Studio (GuideMia Technologies), and Implant Studio (3Shape) [3, 15]. The accuracy of these software packages, however, can be impacted by a range of factors, including the fidelity of cone-beam computed tomography (CBCT) and intraoral optical scanning (IOS) data registration, as well as 3D reconstruction processes and proprietary software algorithms [16, 17]. A comprehensive head-to-head evaluation of different digital platforms is therefore warranted to identify the advantages and shortcomings of each system and clarify which is optimally suited to a given clinical context [18–20]. Although a considerable body of literature has examined the accuracy of various software, studies specifically designed to compare their clinical outcomes and precision in single-tooth implant reconstruction are still sparse [21, 22]. Moreover, when planning fixture insertion, implant length is a pivotal parameter that requires meticulous consideration. Although longer implants might intuitively seem preferable for delivering superior anchorage and load-bearing capacity, evidence suggests they are also associated with a heightened likelihood of positional drift. Against this background, the present retrospective cohort study aimed to quantify the correspondence between virtually planned and surgically achieved implant positions using two of the most frequently adopted implant planning software applications in everyday practice, to explore the placement variation attributable to the choice of software, to furnish evidence-based guidance for rational software selection in the clinical arena, and to scrutinize risk factors that modulate the fidelity of the digital implant insertion workflow. The null hypothesis stated that no statistically significant discrepancy would be detected in the clinical accuracy of the planned relative to the placed implant positions when comparing the two implant planning software applications.

Materials and Methods

Before launching this retrospective cohort study, a survey was conducted to document the relative frequency of use of various implant planning software programs across seven dental laboratories in Wuhan, China, during the period from 2020 to 2023. The survey revealed that among 13,200 cases planned with different software, 3Shape Implant Studio accounted for 7,165 cases [54%] and GuideMia for 4,705 cases [35%], establishing these two as the predominant implant planning software packages in clinical circulation **(Table 1)**.

Table 1. The frequency of different implant planning software programs between 2019 and 2023.

Category	Software system	Utilization rate (%)
Implant planning software used in dental laboratories	3Shape Implant Studio	54
	GuideMia Implant System	35
	coDiagnostiX	5
	SimPlant™	3
	EXOCAD	3

Study design and patient selection

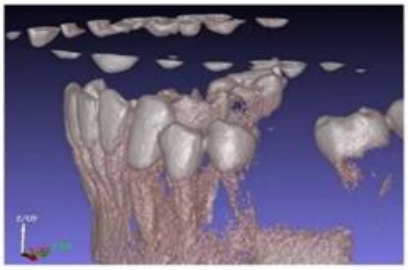
Individuals who underwent implant surgery digitally designed with either the GuideMia implant system or 3Shape Implant Studio by a single operator (S.K) from March 2020 through March 2023 were consecutively screened for potential inclusion. Records of 75 subjects who met all predefined inclusion and exclusion criteria were retrospectively compiled. A cumulative total of 75 fixtures were inserted, distributed as 40 in the GuideMia arm and 35 in the 3Shape arm. A post-hoc power calculation based on this sample size was subsequently performed and returned a statistical power value of 0.66. The retrospective trial registration identifier is ChiCTR2400080259, with a registration date of January 24, 2024.

Eligibility for inclusion required: [1] A single missing tooth confined to the molar or premolar zone (in either the maxilla or the mandible); [2] Availability of a postoperative CBCT scan; [3] A total oral scan count below 1000; [4] Adequate native bone volume at the edentulous site at the operative appointment, with no concomitant bone augmentation procedure; [5] Well-aligned dental arches; and [6] Placement of a bone-level, round-apex implant demonstrating satisfactory primary stability directly after insertion (IOS > 60).

Reasons for exclusion encompassed: [1] Untreated or currently active periodontal pathology; [2] A smoking habit exceeding 10 cigarettes per day; [3] A diagnosed chronic systemic condition; and [4] the intraoral presence of metal-based restorations.

Data acquisition

Upon completion of the preliminary examination, every patient, whose dental arches were kept apart by a cotton roll, underwent a CBCT scan (KaVo Dental, Germany) configured with the following acquisition parameters: 120 kV, 5 mA, 26.9 s, field of view set to 160 mm × 130 mm, and a voxel dimension of 250 µm, to confirm adequate bone availability to accommodate an implant. Oral soft and hard tissue surface scans were recorded using a Trios intraoral scanner (3 Shape TRIOS, Denmark). The unprocessed, raw CBCT volumes in Digital Imaging and Communications in Medicine (DICOM) format, along with the IOS data in Standard Tesselation Language (STL) format, were directly transferred into the implant planning application. The CBCT dataset was subsequently segmented to remove artifacts and extraneous tissue, yielding a virtual 3D representation of only dental hard tissues and alveolar bone. A series of shared landmarks or fiducial reference points, easily discernible in both the STL models and the CBCT slices and situated within the anatomical region of interest, was identified. The program's built-in automated alignment engine then calculated the optimal best-fit superimposition anchored by these defined landmarks. A virtual diagnostic wax-up mimicked the final prosthetic crown on the digital model, accounting for occlusal loading vectors, axial wall emergence, and contact relationships with adjacent teeth. Following the generation of a "digital patient" that integrated the dentition, the supporting bone, and the virtual prosthesis, the specific implant system and dimensions were selected from the software's implant catalog, guided by the prosthetic-driven concept. A protective buffer zone of 2.0 mm was preserved relative to the inferior alveolar nerve canal. A single clinician was responsible for carrying out the entire sequence of implant planning steps. Once the virtual plan was finalized, the designed surgical template was exported as an STL file for physical fabrication. A detailed summary report, listing the osteotomy drill sequence and the corresponding implant specifications, was generated. The surgical guide, incorporating an inspection window, was manufactured with a 3D printer (Evo DentDLP S110), and the system-specific metal reduction sleeve (Ø 5 mm or Ø 3.7 mm T-sleeves) was thereafter inserted into the guide body **(Figures 1 and 2).** Each guide was deliberately extended to encompass 4–6 teeth.



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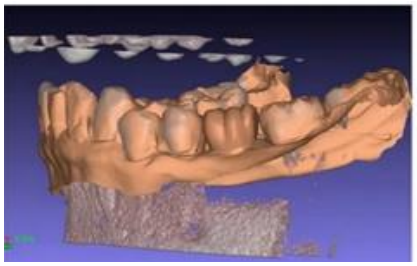

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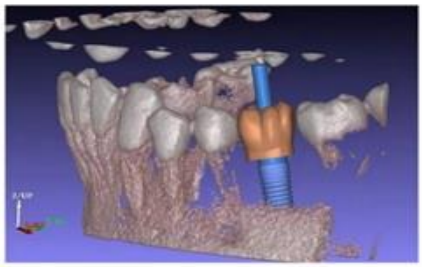

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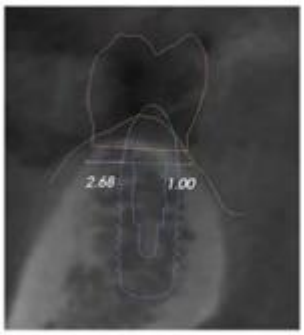

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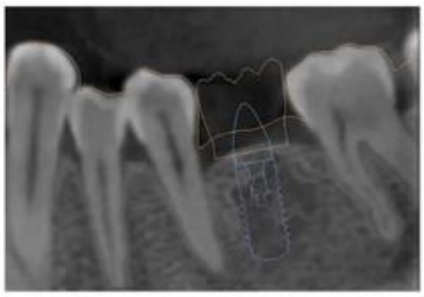

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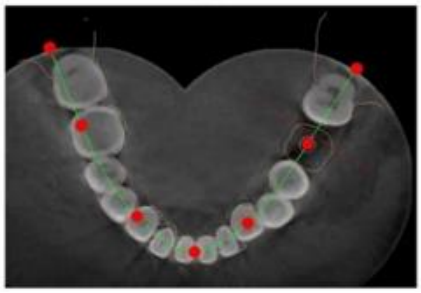

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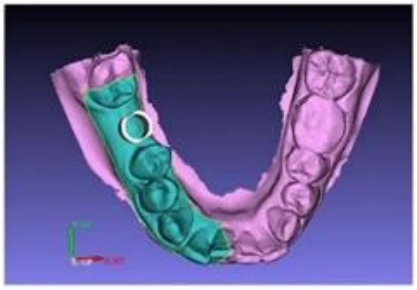

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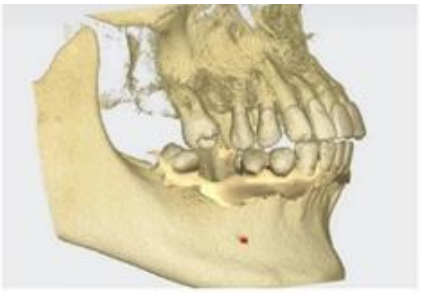
Figure 1. Design of the surgery-guided template in the GuideMia implant system: a) Preoperative CBCT scans were imported into the program package, b) IOS data were matched to CBCT images, and a virtual wax-up was created, c) The implant type and size were selected from the implant library, d) Planned implant placement [coronal view], e) Planned implant placement [sagittal view], f) Planned implant placement [cross view], g) Drawing guide range, and h) 3D printing guide.



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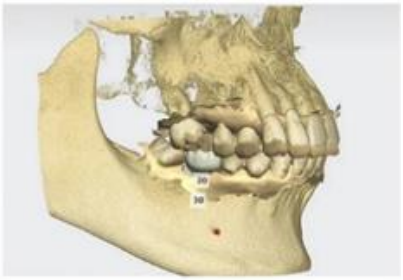

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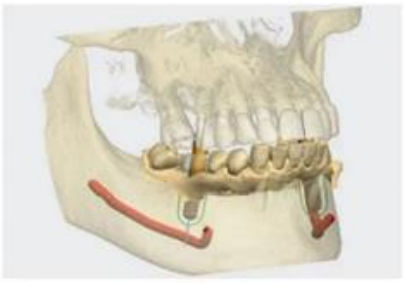

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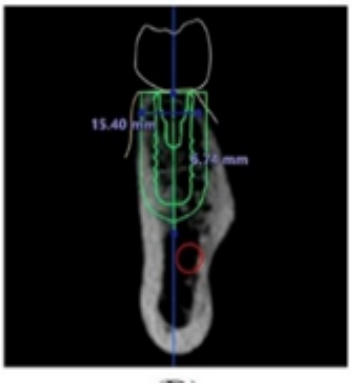

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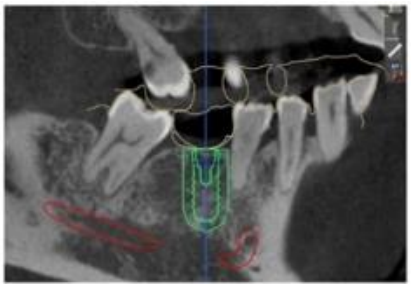

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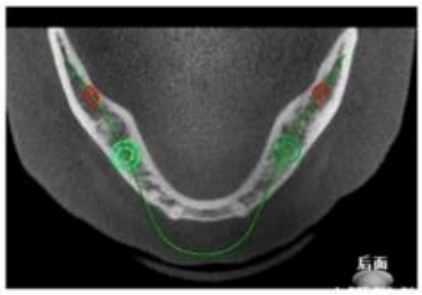

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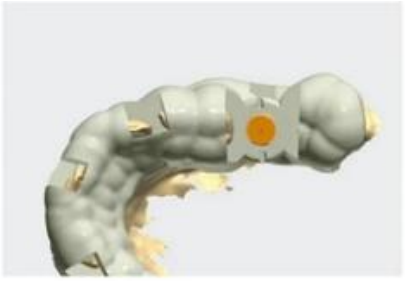

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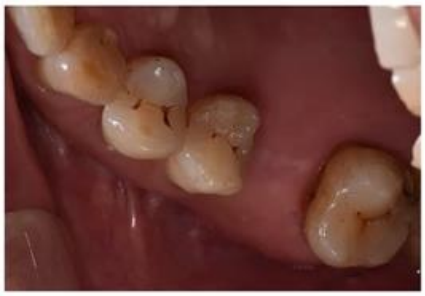
Figure 2. Design of the surgery-guided template in the 3Shape implant studio: a) Preoperative CBCT scans were imported into the program package, b) IOS data were matched to CBCT images, and a virtual wax-up was created, c) The implant type and size were selected from the implant library, d) Planned implant placement [coronal view], e) Planned implant placement [sagittal view], f) Planned implant placement [cross view], g) Drawing guide range, and h) 3D printing guide.

Surgical protocol

Every surgical intervention was performed according to a partially guided workflow by the same clinician who had devised the preoperative digital implant plan, indicating that the surgical template was used solely to guide the osteotomy-drilling steps [13]. Before initiating the surgery, the tooth-borne surgical drill template was carefully positioned, and its intimate fit was verified. The implant placement was performed via an open-flap technique, and the manufacturer's prescribed guided surgical drilling progression was adhered to to complete the osteotomy site preparation. All implants were inserted as single-stage fixtures and were permitted to heal via a transmucosal approach **(Figure 3).** Patients were advised to consume only soft foods for 1 week and to avoid touching the surgical areas when brushing. They additionally received a prescription for ibuprofen 600 mg to be taken every six hours throughout the first 48 hours to control any potential pain. They were instructed to rinse the oral cavity twice daily with a chlorhexidine-based mouthwash for 2 weeks postoperatively. The implants placed ranged in diameter from 3.3 to 4.8 mm, while the chosen lengths were 8, 10, and 12 mm (Institut Straumann AG, Basel, Switzerland, and Axiom REG France).



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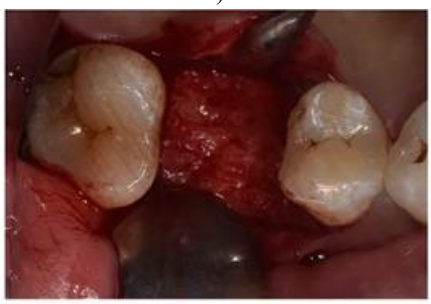

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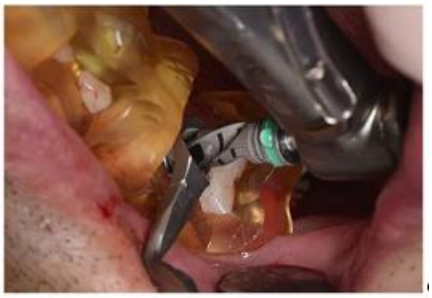

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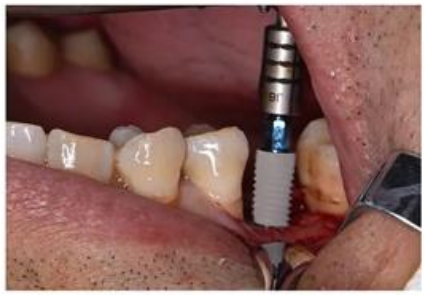

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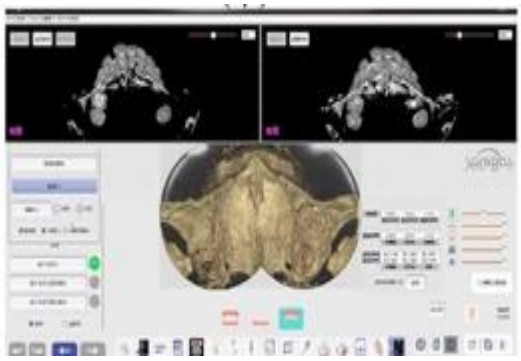
Figure 3. Surgical process with partial guided protocol: a) Preoperative occlusal view, b) Occlusal view after the open flap, c) Implant drill sequence with the surgical guide, d) The direction of the prepared hole, e) The implant [Straumann BL, Switzerland] was inserted after continuous drilling, and f) Install healing abutment

In vivo accuracy assessment

Directly following the surgical intervention, a further CBCT acquisition was performed [120 kV, 5 mA, 26.9 s, FOV: 160 mm × 130 mm, voxel dimension: 250 µm, section thickness: 0.25 mm]. The DICOM datasets originating from both the postoperative and preoperative scans, with embedded virtual treatment plans, were transferred to an independent evaluation software platform [DentalNavi; YakeRobot Technology Ltd] [23]. The superimposition workflow was triggered by activating the "Align CT" tool. This step called for identifying and marking three uniformly distributed, mutually recognizable anatomical landmarks or fiducial points that could be consistently localized in both CBCT volumes to finalize co-registration. Thereafter, the "Align Implant" tool was engaged by highlighting the implant representation within the postoperative CBCT volume. The workflow concluded by selecting "Generate Report," after which the application rendered a comparative overlay of the preoperative design and the postoperative reality and issued an electronic report containing a three-dimensional deviation analysis tailored to each subject **(Figures 4 and 5).** This superimposition methodology was grounded in the image-based best-fit algorithm (ICP (Iterative Closest Point) surface registration). To gauge accuracy, the three ensuing outcome variables were logged: 3D linear deviation at the coronal and apical landmarks, expressed in millimeters, and angular deviation of the fixture, expressed in degrees **(Figure 6).** Coronal deviation was defined as the Euclidean distance between the planned and actual implant platform centers. Apical deviation denoted the Euclidean distance separating the planned implant apex center from the actual implant apex center. Angular deviation is the angle subtended by the longitudinal axes of the two implants. Each case underwent three separate measurement cycles by a single examiner, and the average value was used. Beyond this, the intra-class correlation coefficient (ICC) figures calculated for these measurements consistently exceeded the 0.9 threshold, underscoring strong measurement dependability.



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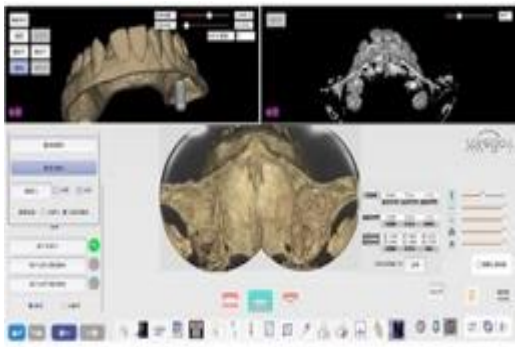

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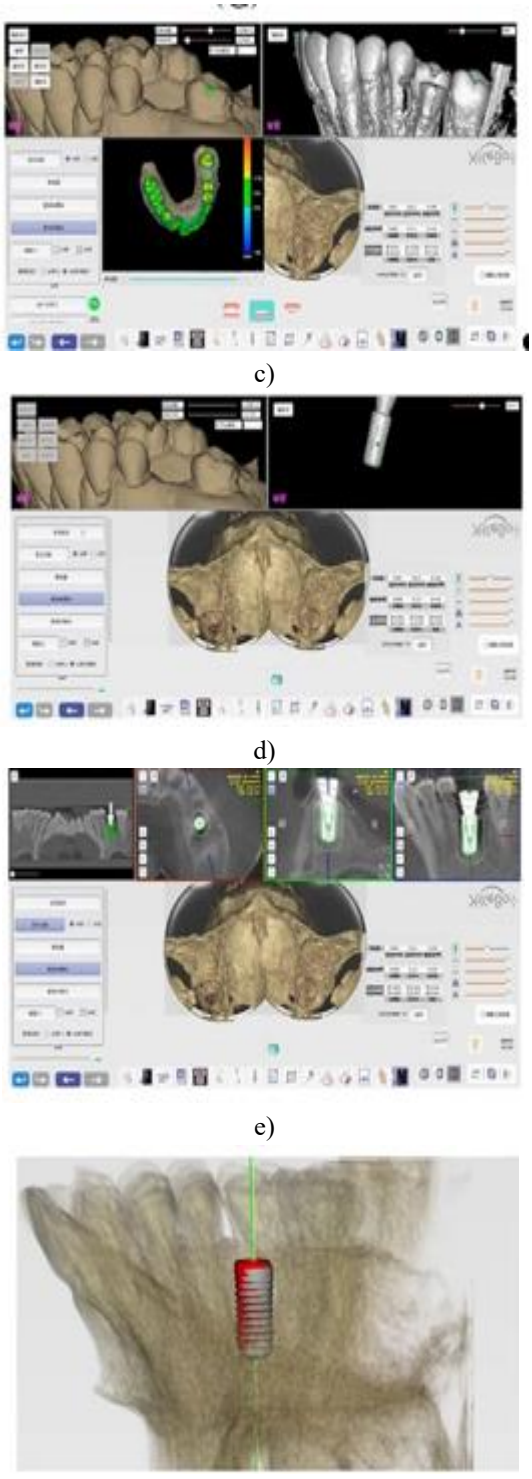

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Figure 4. a, b) Postoperative and preoperative CBCTs with virtual planning were imported into dentalNavi, c, d) Registration of scans and implants, e, f) The 3D view of the preoperative plan compared with the postoperative CT.

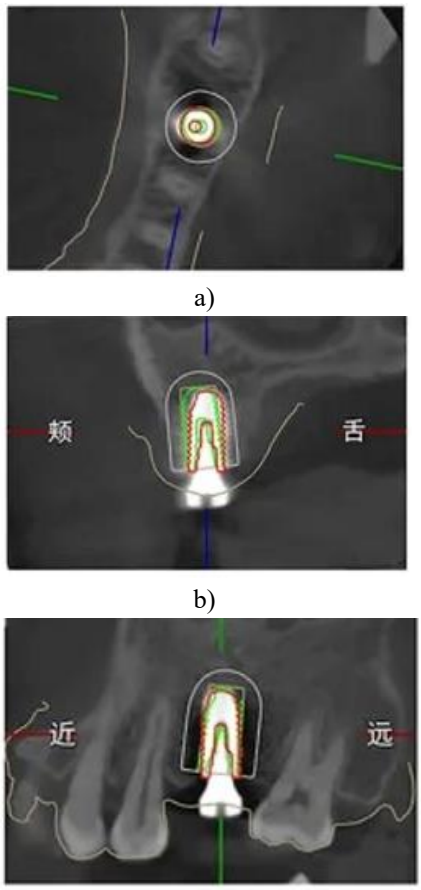

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Figure 5. a-c) Postoperative evaluation: comparing the accuracy of preoperative [green] with postoperative actual implant position [red].

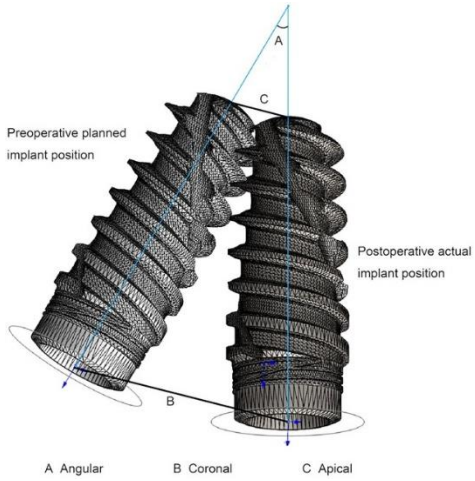

Figure 6. Schematic diagram of the deviation between planned and actual implant positions.

The prognostic risk factors hypothesized to independently alter the fidelity of guided implant surgery were specified and categorized as follows: implant length (8, 10, 12 mm)], implant diameter (3.3, 4, 4.1, 4.6, 4.8 mm), the intra-arch location of the recipient site (premolar or molar), the arch position of the recipient site [maxilla or mandible], implant system

(Straumann BL or Axiom REG), and free-end edentulous condition (Yes, No).

Statistical analysis

The full complement of statistical computations was carried out within the SPSS for Windows Release 27 environment (SPSS Inc., Chicago, IL, USA), with the alpha criterion set to 0.05. Accuracy endpoints were scrutinized at the unit implant level, and descriptive summaries were rendered as the mean value plus/minus the standard deviation [±]. For univariate screening of risk factors, a two-tailed independent t-test was used for dichotomous variables. In contrast, a one-way analysis of variance was used for variables with three or more categories. Because the risk factors of arch, intra-arch site, implant system, diameter, and length were interrelated, a multiple linear regression analysis was conducted to disentangle the specific contributions of individual risk determinants to the documented deviations. The influence exerted by categorical predictors was accommodated within the regression framework by coding them as dummy variables.

Results and Discussion

Patient information

Taken together, 59 implants were placed in the mandible and 16 in the maxilla. Regarding the implant brand, 49 fixtures were from the Straumann BL family and 26 from the Axiom REG family. The length distribution across the sample was as follows: 8 mm in 16 patients, 10 mm in 49 patients, and 12 mm in 10 patients. For implant diameter, the figures stood at 3.3 mm in 4 patients, 4 mm in 7 patients, 4.1 mm in 15 patients, 4.6 mm in 16 patients, and 4.8 mm in 33 patients. In addition, 20 fixtures occupied premolar sockets, 55 occupied molar sockets, and 22 were situated in free-end configurations. **Table 2** presents an overview of the implant descriptive characteristics and their placement circumstances. No statistically significant divergence was observed in any of these baseline variables between the two groups ($P > 0.05$).

Table 2. Characteristics and position of placed implants between the guideMia and 3Shape systems.

Variable	GuideMia	3Shape	Overall	P-value
Implant diameter	—	—	—	0.853[b]
Narrow [3.3 mm]	1	3	4	—
Standard [4.0 mm]	7	3	7	—
Standard [4.1 mm]	5	7	15	—
Standard [4.6 mm]	15	8	16	—
Standard [4.8 mm]	12	21	33	—
Implant system	—	—	—	0.163[a]
Straumann	20	29	49	—
Axiom	15	11	26	—
Implant length	—	—	—	0.921[b]
8 mm	7	9	16	—
10 mm	28	21	49	—
12 mm	5	5	10	—
Distal extension [free-end edentulism]	—	—	—	0.378[a]
Yes	10	12	22	—
No	30	23	53	—
Jaw location	—	—	—	0.407[a]
Maxilla	10	6	16	—
Mandible	30	29	59	—
Tooth position	—	—	—	0.222[a]
Premolar	13	7	20	—
Molar	27	28	55	—

a Differences between groups were analyzed using Pearson's chi-squared test.
b Differences between groups were analyzed using Fisher's exact test.

Implant deviation comparison

Focusing on the GuideMia cohort, the mean coronal, apical, and angular discrepancies were 1.16 mm, 1.79 mm, and 3.60°, respectively, for the 8 mm implant length subset. In the 10 mm length subset, the corresponding values reached 1.10 mm, 1.20 mm, and 4.45°, whereas in the 12 mm length subset, they measured 0.95 mm, 1.38 mm, and 5.25°. Turning to the 3Shape cohort, the parallel discrepancies for the 8 mm subset were 0.88 mm, 1.27 mm, and 3.96°. Among 10 mm implants, the data showed 1.06 mm, 1.08 mm, and 3.67°, and in the 12 mm group, the figures were 0.59

mm, 0.80 mm, and 3.13°. Across all implant length tiers, no statistically significant differences emerged between the two implant planning software platforms for any of these outcome measures (P > 0.05) **(Table 3).**

Table 3. Deviation of the actual implant position and the planned implant position between the GuideMia and 3Shape systems.

Group	Sample size [N]	Coronal deviation [mm]	Apical deviation [mm]	Angular deviation [°]
[1] Implants with 8 mm length				
GuideMia	7	1.16 ± 0.34	1.79 ± 0.66	3.60 ± 1.92
3Shape	9	0.88 ± 0.46	1.27 ± 0.51	3.96 ± 2.20
t-statistic	—	1.30	1.76	0.34
p-value	—	0.21	0.09	0.73
[2] Implants with 10 mm length				
GuideMia	28	1.10 ± 0.42	1.20 ± 0.59	4.45 ± 2.49
3Shape	21	1.06 ± 0.72	1.08 ± 0.51	3.67 ± 2.67
t-statistic	—	0.22	0.73	1.05
p-value	—	0.82	0.46	0.29
[3] Implants with 12 mm length				
GuideMia	5	0.95 ± 0.72	1.38 ± 0.75	5.23 ± 2.77
3Shape	5	0.59 ± 0.13	0.80 ± 0.21	3.13 ± 2.16
t-statistic	—	1.08	1.64	1.33
p-value	—	0.33	0.13	0.21

Risk factor analysis

A series of statistically significant relationships emerged from multiple linear regression analyses of individual predictors hypothesized to affect guided implant placement fidelity. All constructed models satisfied the fundamental assumptions of linearity, independence of observations, homoscedasticity, and normal distribution of residuals. The coefficients of determination [R^2] reached 0.163 for coronal deviation, 0.164 for angular deviation, and 0.211 for apical deviation, suggesting that the fitted models explained a modest yet appreciable portion of the variance in the data. The regression output indicated that the choice of arch [maxilla or mandible], the implant manufacturer, the intra-arch site [premolar or molar], and the implant's dimensional characteristics—both diameter and length—were not significant predictors (P > 0.05). By marked contrast, a strong statistical signal differentiated free-end from bounded-saddle implant placements across all three axes of measurement: at the entry point (P = 0.003), at the apical endpoint (P = 0.005), and in angular orientation (P = 0.002). The full set of candidate risk factors, together with their associated mean values, is presented in **Table 4.**

Table 4. Results of the multivariate analysis per risk factor.

Risk variable	N	Coronal deviation [mm]			Apical deviation [mm]			Angular deviation [°]		
		Mean	SD	P-value	Mean	SD	P-value	Mean	SD	P-value
Implant diameter				0.54			0.34			0.06
Narrow [3.3 mm]	4	1.16	0.78	—	1.15	0.60	—	4.11	3.34	—
Standard [4.0 mm]	7	1.21	0.67	—	1.05	0.57	—	5.26	1.64	—
Standard [4.1 mm]	15	0.83	0.50	—	1.09	0.54	—	2.71	0.74	—
Standard [4.6 mm]	16	1.05	0.40	—	1.18	0.53	—	3.56	2.09	—
Standard [4.8 mm]	33	1.05	0.56	—	1.20	0.62	—	4.64	2.88	—
Implant system				0.30			0.40			0.95
Straumann	49	0.98	0.57	—	1.17	0.59	—	3.95	2.74	—
Axiom	26	1.12	0.46	—	1.29	0.59	—	3.91	2.15	—
Implant length				0.23			0.09			0.90
8 mm	16	1.00	0.42	—	1.50	0.62	—	3.68	2.12	—
10 mm	49	1.09	0.56	—	1.15	0.56	—	4.01	2.66	—
12 mm	10	0.77	0.52	—	1.09	0.60	—	4.98	2.76	—
Distal extension [free-end edentulism]				0.003			0.005			0.002
Yes	22	1.31[a]	0.64	—	1.51[a]	0.72	—	5.37[a]	3.08	—

No	53	0.91[a]	0.44	—	1.09[a]	0.48	—	3.51[a]	1.90	—
Jaw				0.70			0.30			0.84
Maxilla	16	0.98	0.60	—	1.08	0.63	—	4.05	3.39	—
Mandible	59	1.04	0.52	—	1.25	0.57	—	3.91	2.29	—
Tooth location				0.62			0.44			0.57
Premolar	20	1.08	0.63	—	1.30	0.62	—	3.79	2.13	—
Molar	55	1.01	0.50	—	1.18	0.58	—	4.15	2.55	—

a Significantly different in the multivariate analysis.

Implant planning platforms can substantially assist operators in localizing the ideal implant coordinates in line with the "prosthetic-driven" philosophy and in translating that plan into surgical reality through static drilling guides or dynamic navigation systems [24, 25]. Our data revealed that, when fixtures of equivalent length were considered, no meaningful accuracy gap was observed between the two software solutions in the concordance between planned and executed implant positions. Consequently, the null hypothesis stands. Benchmarking our observations against aggregated estimates from contemporary systematic reviews and meta-analyses of clinical trials, the reported average displacement at the implant shoulder spans roughly 1.1–1.4 mm, apical displacement lies in the vicinity of 1.2–1.6 mm, and axial angular deflection approximates 3.0°–4.3° [26, 27]. The measurements obtained in the present work fall comfortably within these published norms. Since the apical drift documented in both software programs remained confined to the 1.0–1.5 mm band, a 2 mm vertical buffer zone should provide ample safety.

Nonetheless, the 3Shape Implant Studio and the GuideMia implant system each have unique strengths and weaknesses. The GuideMia ecosystem is purpose-built around implant surgical planning and execution, delivering a thoroughgoing toolset for virtual fixture positioning and surgical guide design. The 3Shape environment, by contrast, is conceived to integrate natively with intraoral scanning hardware and supplies a wide-ranging suite of dental CAD/CAM functions, spanning digital impression workflows, laboratory-based prosthetic design, and guide manufacturing pipelines [15, 28]. The decision between the two ultimately rests on the user's specific clinical demands and personal workflow preferences. Operators whose practice is concentrated predominantly on implant therapy may perceive GuideMia as a closer match to their niche requirements.

In contrast, those pursuing a more versatile, all-encompassing dental CAD/CAM solution may gravitate toward 3Shape. A second point of divergence lies in the user experience: GuideMia demands a considerable investment in training. Its densely layered interface and multi-step operational flow compel users to traverse an array of menus, instrument sets, and configuration options to accomplish discrete tasks—especially throughout the guide-design module. Numerous critical judgments concerning virtual implant positioning must be made by the operator without heavy automation. This complexity can prove daunting to inexperienced users, who may need to invest substantial time and effort before achieving a fluent, efficient command of the program.

In contrast, 3Shape showcases an accessible, ergonomically designed interface that is both intuitive and easy to navigate. It presents a refined, step-by-step workflow that attentively escorts users through each successive phase via lucid on-screen guidance and contextual prompts. A third differentiator concerns economics: the purchase price and licensing fees for GuideMia and 3Shape fluctuate based on the chosen software bundle, supplementary modules, and subscription model. GuideMia is positioned as a budget-conscious option, a factor that has boosted its uptake among smaller-volume dental practices. 3Shape, being an end-to-end CAD/CAM ecosystem, is typically associated with a heftier investment. Both platforms, however, boast broad interoperability with numerous implant families, a feature that streamlines tripartite collaboration among dental laboratories, treating clinicians, and implant manufacturers. On balance, practitioners would be well advised to carefully survey their individual clinical priorities and weigh the aforementioned considerations when selecting between these platforms [29, 30]. It bears emphasis that the feature sets and relative advantages described here are fluid and will likely shift as the respective companies iteratively update their products and roll out new functionalities. The foremost strength of this investigation is the unbiased, side-by-side comparison of two implant design ecosystems conducted using independent third-party metrology software. This design choice substantially reduced measurement bias and enabled an equitable assessment of the positional discrepancies inherent to each system. Among the study's constraints are incomplete standardization of baseline demographic and clinical covariates across the two arms, as well as the inherent selection and information biases endemic to

retrospective research. Such factors may have introduced residual confounding, tempering the precision of inter-software performance contrasts. Future prospective work should prioritize the formulation of stringent eligibility criteria that systematically account for effect modifiers, such as regional bone quality, diverse implant recipient locations, and operator experience strata, to extract findings that are both robust and broadly applicable. Furthermore, although entrusting all surgical procedures to a single clinician curtails inter-operator variability in technique and promotes a uniform procedural methodology, this design choice simultaneously risks embedding systematic operator-specific bias, as operative results may be shaped by that individual's personal clinical experience, technical aptitude, and intraoperative discretionary choices. Future investigations would benefit from enrolling multiple surgeons to enhance the external validity of the conclusions and provide corroborative evidence across a wider spectrum of clinical settings.

The variation documented in the fidelity of guided implant surgery has been chiefly ascribed to errors arising from both intrinsic and extrinsic origins [31–33]. Intrinsic errors encompass inaccuracies embedded in the guide design or manufacturing process, flaws in software algorithms, constraints inherent to imaging technology, and misregistration between CBCT and IOS datasets. Extrinsic errors, on the other hand, stem from the surgeon's technique, the patient's individual anatomy, and the intraoperative behavior of the surgical guide. In the present investigation, we restricted enrollment to individuals with well-aligned dental arches, no metal-based restorations, and high-fidelity intraoral optical scans. A single experienced operator executed the entire workflow to minimize preoperative design inaccuracies. A discernible improvement in accuracy was observed in single-implant cases in bounded edentulous spaces. This observation implies that free-end scenarios may increase the difficulty of achieving the preoperatively planned implant coordinates, given the lack of a distal abutment tooth to provide support and spatial reference. By comparison, non-free-end gaps can supply additional stabilization and fiduciary landmarks to guide implant positioning. In line with the report by Sigcho Lopez *et al*. [34], the surgical template may undergo subtle displacements during the osteotomy sequence, and employing a guide that relies on only one side risks magnified implant deviations due to guide tilting and flexure. El Kholy *et al*. [35] demonstrated in a bench-top study that fixtures inserted into distal extension locations displayed significantly greater entry-point and apical discrepancies than those placed with a bilateral tooth-supported guide. This underscores that, when planning an implant in a free-end site, stability can be bolstered either by refining the precision of the surgical template to guarantee an intimate fit against the dental arch or by extending the guide to envelop additional teeth, thereby harnessing maximal support from the adjacent dentition [36]. Moreover, longer fixtures can pose a greater technical challenge for accurate positioning owing to the heterogeneity in bone density and quality encountered along the prepared osteotomy, which complicates achieving an ideal placement trajectory. Longer implants may also require greater surgical dexterity and experience, as the added length can make it more difficult to control the spatial positioning and axial inclination of the fixture during insertion. Having said that, the risk factor analysis conducted in this study failed to detect any measurable effect of varying implant length on accuracy. This null finding may be attributable to the limited sample size, underscoring the need for subsequent investigations with larger cohorts to substantiate these results. Furthermore, the constraints associated with pre- and postoperative CBCT superimposition warrant acknowledgment. First, metallic artifacts originating from the implant body and prosthetic components can blur the bone-implant interface, undermining the fidelity of long-axis determination and potentially introducing measurement bias. Second, post-extraction alveolar remodeling and ridge resorption diminish the extent of stable hard-tissue surface available for dependable registration. Lastly, the intrinsic registration error (on the order of 0.1–0.5 mm) inherent to surface-based matching algorithms may obscure minor inter-system deviations.

In the present work, implants with a rounded apical architecture were employed, a design that may be more prone to deflection by the crestal bone or the cortical housing, potentially resulting in positional inaccuracies. Conversely, fixtures endowed with a more assertive apical thread configuration may enhance engagement with denser cortical layers, thereby promoting both stability and precision during the insertion phase [37]. Beyond this, several investigators have noted that fully guided surgical templates achieve greater accuracy than their partially guided counterparts [13, 38, 39]. Accordingly, further experimental work is warranted to contrast and quantify the deviation in accuracy between these divergent guidance modalities.

Notwithstanding the encouraging outcomes of CAD software deployment, a degree of residual deviation

persists. For this reason, advancing the performance of the various hardware components and software platforms involved remains an imperative. As scholarly inquiry into the fully digital workflow continues to mature, increasingly refined data-acquisition instruments will emerge, and clinicians will correspondingly hone their ability to manage and mitigate errors at every link of the digital chain.

Conclusion

No statistically significant difference in implant position accuracy was observed between the GuideMia implant system and the 3Shape Implant Studio platform. Practitioners are encouraged to thoughtfully assess their specific clinical requirements and weigh pertinent factors when choosing practical application. In addition, implants situated at the distal extension of the dental arch, where bilateral adjacent teeth to brace the drilling guide are absent, exhibited magnified deviations at both the apical and entry-point landmarks. Continued refinement of the fully digital workflow to deliver incremental improvements in placement fidelity is advised.

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