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ORIGINAL ARTICLE

Accuracy of automatic and manual dynamic navigation registration techniques for dental implant surgery in posterior sites missing a single tooth: A retrospective clinical analysis

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Abstract

Objectives: To assess the relative accuracy of manual (U-shaped tube) and automatic (two-in-one) dynamic navigation registration techniques for implant surgery performed in posterior sites missing one tooth.

Materials and Methods: This study included 58 partially edentulous patients with 58 implants, including 31 and 27 in the manual and automatic groups. Deviations between the planned and actual implant placement were assessed.

Results: The angular deviation in the overall study cohort was 2.54 ± 1.21°, while the 3D deviations at the implant platform and apex were 0.90 ± 0.46 mm and 1.04 ± 0.47 mm, respectively. The respective angular deviations in the manual and automatic groups were 2.82 ± 1.17° and 2.21 ± 1.19° ($p > .05$), while platform deviations were 0.89 ± 0.48 mm and 0.91 ± 0.45 mm ($p > .05$), and apex deviations were 0.99 ± 0.48 mm and 1.11 ± 0.46 mm ($p > .05$). No significant differences in absolute buccolingual, mesiodistal, or apicocoronal deviations were detected between these groups at either level ($p > .05$) nor were did deviation distributions differ in the buccolingual, mesiodistal, or apicocoronal directions at the platform or apex levels ($p > .05$).

Conclusions: Manual and automatic dynamic navigation registration techniques can achieve excellent accuracy when placing implants in posterior sites missing a single tooth. The two-in-one automatic registration technique can reduce the amount of time and intraoperative steps necessary to complete the registration process relative to the manual U-shaped tube registration technique. Further follow-up studies are necessary to expand on these results.

KEYWORDS
accuracy, dynamic navigation, implant surgery, registration method, registration-and-fixation, two-in-one, U-shaped tube

1 | INTRODUCTION

The three-dimensional (3D) positioning of a dental implant influences its long-term postoperative stability (Buser et al., 2004; D'Haese et al., 2017; Tarnow et al., 2000). Variations in the experience levels of operating physicians will ultimately lead to variability with respect to implant positioning during freehand implantation procedures, potentially resulting in short- or long-term postoperative complications (Romanos et al., 2019). As such, accurately achieving the planned preoperative positioning of a dental implant is vital to ensure optimal

patient outcomes. Both static and dynamic computer-assisted implant surgery (sCAIS and dCAIS) approaches have been developed as approaches to reducing intraoperative deviations from planned implant positioning, thus ensuring that these implants can be safely and accurately placed within the target operative area (Chen et al., 2020; Gargallo-Albiol et al., 2019).

Relative to freehand implant placement, both sCAIS and dCAIS can achieve higher levels of accuracy (Aydemir & Arısan, 2020; Gargallo-Albiol et al., 2019; Jorba-García et al., 2021; Pellegrino et al., 2021; Wei et al., 2021). The dCAIS approach is also more flexible and allows for better visualization relative to sCAIS approaches, allowing for better drill cooling in addition to being less impacted by the opening of the mouth or intraoperative adjustments to implant design, allowing preoperative protocol development and operative procedures to be completed within a single day (D'Haese et al., 2017; Gargallo-Albiol et al., 2019; Jorba-García et al., 2021).

The accuracy of dCAIS procedures is highly dependent on appropriate registration (Widmann et al., 2010). In cases of partial edentulism, two dCAIS registration techniques have been developed: anatomical point registration (APR) and marker point registration (MPR). APR entails registration based on the cusp or fossa of teeth (Ma et al., 2022; Stefanelli et al., 2020; Wang et al., 2022), whereas MPR employs a registration marker device (Block, Emery, Cullum, et al., 2017; Block, Emery, Lank, et al., 2017; Chen et al., 2018; Wu et al., 2020). In vitro, the MPR approach is reportedly more accurate than the APR approach (Kang et al., 2013; Pei et al., 2022; Wang et al., 2022), while a single retrospective analysis reported these two techniques to exhibit similar accuracy (Ma et al., 2022).

In both clinical and training settings, the use of a U-shaped tube device is among the most common MPR strategies employed for the placement of dental implants (Chen et al., 2022; Ma et al., 2022; Wei, Li, et al., 2022; Wei, Shi, et al., 2022; Wu et al., 2020; Yao et al., 2022; Zhan et al., 2021). This device consists of an occlusal splint supported by the teeth, with silicone rubber being used to fix the U-shaped tube registration device in the site of this missing tooth. This method is highly accurate and noninvasive but requires intraoperative point-to-point manual registration (MR) for a minimum of six points. This device is also associated with other disadvantages including: (1) the registration procedure is relatively time-consuming, (2) the procedure entails a significant learning curve, (3) the U-shaped tube device may exhibit poor stability in partially edentulous arches with a distal extension, (4) the registration device is somewhat large and can thus cause a foreign body sensation while placed in the mouth, and (5) the registration process necessitates the positioning of a registration device in the site of the missing tooth as well as a fixation device with the reference device on different sides of the same jaw.

The so-called two-in-one registration-and-fixation devices can accomplish both the registration and fixation processes in an automatic manner (Wu & Sun, 2022). This two-in-one device is also smaller than U-shaped tube registration devices, allowing for reductions in consumable use while also dramatically shortening the time and complexity of intraoperative registration procedures. The learning curve associated with this extraoral registration technique is also gentler than that for the U-shaped tube device, and this approach is often highly tolerable for treated patients.

As these two registration techniques rely on distinct mechanisms, they also exhibit varying levels of accuracy. This retrospective study was thus designed to explore the relative accuracy of these two dynamic navigation system registration approaches when placing an implant in posterior sites missing a single tooth, with the null hypothesis that the accuracy of the two-in-one group was inferior that of the U-shaped-tube group when non-inferiority margins (0.31 and 0.49 mm) were employed for dCAIS.

2 | MATERIALS AND METHODS

2.1 | Study design

This was a retrospective study conducted from October 2019 to August 2021 at the First Clinical Division of Peking University Hospital of Stomatology. This study was approved by the Institutional Review Boards of the Peking University School and Hospital of Stomatology (Approval Number: PKUSSIRB-202165090) and registered with the Chinese Clinical Trial Registry (ChiCTR2200065668). The goal of this analysis was to assess the relative accuracy of dynamic registration performed using either a U-shaped tube or two-in-one method in patients undergoing the placement of dental implants in posterior sites missing a single tooth. Primary study outcomes included platform deviation, apex deviation, and angular deviation between the planned and actual positioning of the implant. This study was performed as per the 2013 revision of the Helsinki Declaration and complied with the STROBE checklist. All patients provided written informed consent.

2.2 | Subject criteria

Participants were eligible for inclusion when they met the following criteria: (1) patients where fully dynamic navigation was used for implant placement; (2) patients with implants positioned in posterior molar or premolar sites missing a single tooth; and (3) the implant placement was conducted via either a U-shaped tube or two-in-one registration device. Patients were excluded if they exhibited maxillary posterior teeth necessitating maxillary sinus lift or underwent implant placement in the edentulous jaw (Figure 1).

2.3 | Preoperative preparation

All patients in the U-shaped tube cohort underwent cone-beam computed tomography (CBCT) scanning (Carestream 9300, Carestream Health) with the following settings: 90 kV, 8 mA, 8 s, and voxel size: 180 μm. Before scanning, the U-shaped tube registration device was affixed in the site of the missing tooth using silicone rubber (DMG Chemisch-Pharmazeutische; Figure 2a,b). Patients in the two-in-one

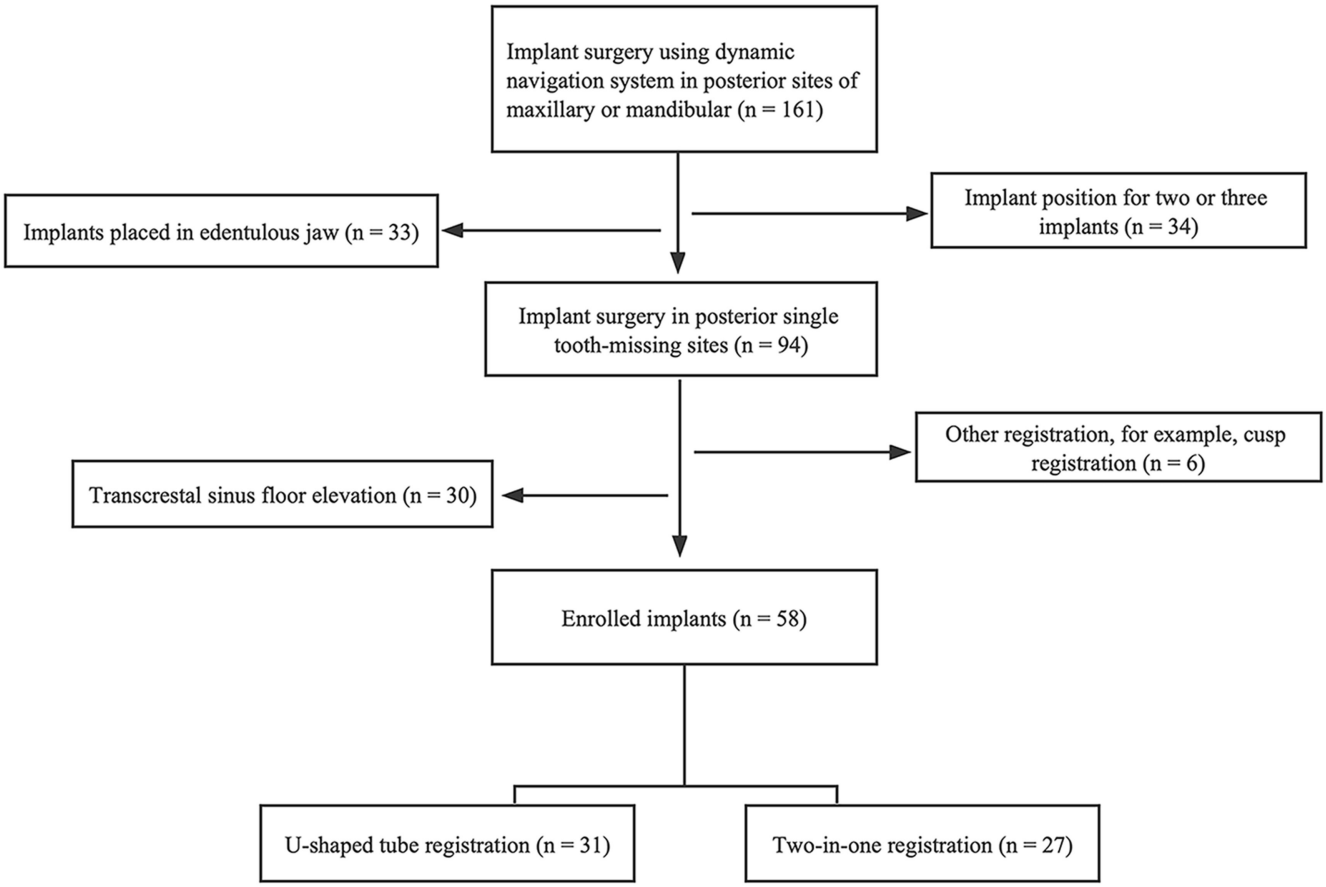

FIGURE 1 Flowchart of patient enrollment.

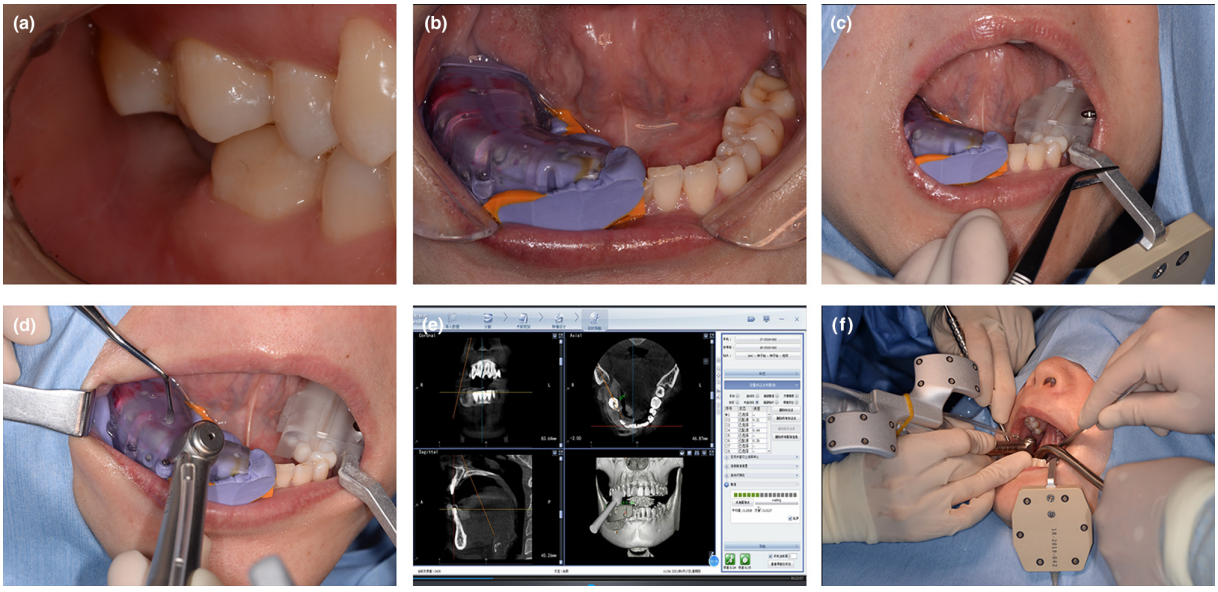

FIGURE 2 U-shaped tube registration method: (a) the edentulous area of a 40-year-old female (tooth 47 missed); (b) a U-shaped tube registration device fitted in the surgical site prior to CBCT imaging; (c) the U-shaped tube registration device and the reference device with the fixation device placed on the patient intraoperatively; (d) U-shaped tube registration; (e) U-shaped tube registration in software; and (f) implant surgery under the dynamic navigation system.

registration cohort similarly underwent CBCT scanning using the same instrument and consistent settings: 90 kV, 8 mA, 8 s, and voxel size: 180 μm. Prior to CBCT imaging, the two-in-one device containing three reflective radiographic marker patches was fixed in the anterior teeth area using thermoplastic resin (DMG Chemisch-Pharmazeutische; Figure 3a,b). Digital CBCT data were imported

into the Dcarer® dynamic navigation software, and implant positioning was then selected. The system implant library was used to choose the optimal length, apical diameter, and platform diameter of the implant to allow for appropriate virtual 3D implant positioning. A single operator experienced with this program performed all preoperative virtual implant planning.

2.4 | Surgical procedures

2.4.1 | U-shaped tube registration

A handpiece locator and reference device equipped with infrared transmitters were initially used for handpiece calibration. These devices transmit a signal to the navigator to facilitate appropriate spatial localization. Long and short ball drills are then consecutively installed on the handpiece, and the spherical portion of the drilling needle is then positioned proximal to a hemispherical groove present on the reference device. Signals emitted by the handpiece locator and reference device are then collected by the navigator and used to establish the positional relationships of these devices.

Next, registration is performed by utilizing self-curing resin (DMG Chemisch-Pharmazeutische) to place a reference device with a fixation device on the opposite side of the same jaw (Figure 2c). After resetting the U-shaped tube registration device within the mouth, the handpiece is equipped with a short ball drill and utilized to collect specific ball pit information for six marker points using the U-shaped tube registration device (Figure 2d,e). After this information has been collected, the relative spatial relationships of the handpiece, reference device, virtual CBCT, and jaw position can be established. When this is completed, the U-shaped tube device is removed, and the accuracy of this registration procedure is assessed by placing a drill on the cusp of the tooth. Surgeons can then visualize the implant and drills in 3D in real time while performing the operation, with the implant and drills being used with a dynamic navigation system (Model: DHC-DI2, Suzhou Digital-health care Co., Ltd.) guidance (Figure 2f).

2.4.2 | Two-in-one registration

Handpiece calibration was initially performed using the same approach as above. The subsequent registration process can be automated in 10–20 s by using a reference device positioned outside the mouth together with three reflective patches present on the two-in-one device. During the operation, a rigid rod is used to connect the reference and two-in-one devices, after which an infrared transmitter placed on the reference device and the two-in-one device's reflective patches are aligned with the navigator throughout the process of registration (Figure 3c,d). The reference device transmitter then emits an infrared signal to the navigator, which in turn emits an infrared signal that is reflected by the reflective patches on the two-in-one device (Figure 3e). When registration is complete, the two-in-one device and associated reference device are reset on the dentition as appropriate, and spatial relationships between the handpiece, reference device, CBCT output, and jaw coordinates can be assessed. The accuracy of this registration is then assessed by placing a drill on the cusps of teeth and the teeth surfaces. Once positional accuracy has been verified, the implant placement procedure can be conducted with a dynamic navigation system (Model: DHC-DI2, Suzhou Digital-health care Co., Ltd.; Figure 3f).

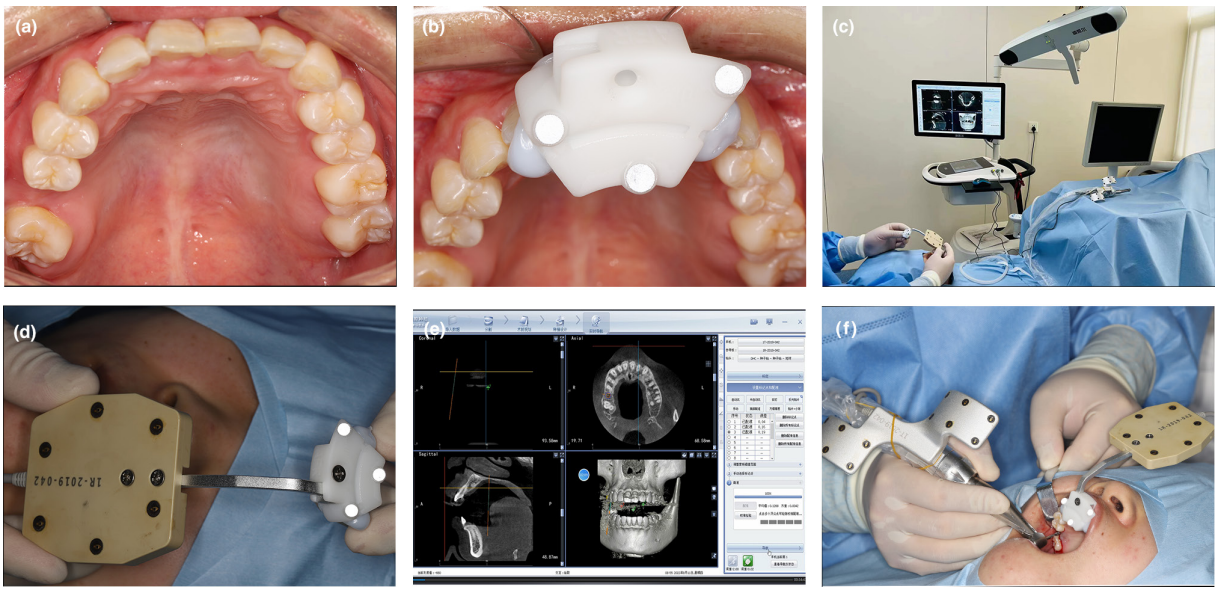

FIGURE 3 Two-in-one registration method: (a) the occlusal view of a 26-year-old female (tooth 16 missed); (b) a two-in-one registration device fitted in the anterior teeth area prior to CBCT imaging; (c) two-in-one registration outside the mouth; (d) connecting the reference device with the two-in-one registration device; (e) two-in-one registration in software; and (f) implant surgery under the dynamic navigation system.

2.5 | Accuracy analyses

Immediately after implant surgery, patients underwent CBCT scanning. An expert blinded to sample identities then matched the planned preoperative and actual postoperative implant positions for these patients with the Dcarer® dynamic navigation accuracy verification software in order to compare deviations between these positions. Nine different effective deviations were analyzed including angular, 3D, mesiodistal, buccolingual, and apicocoronal deviations at the platform and apex of the implant (Figure 4).

The operational process used by the accuracy verification software was as follows:

a. Rough registration steps: four or more characteristic points (such as the cusp or fossa of the teeth or the bone pit) were selected on preoperative and postoperative CBCT, and the best mapping of the two groups using one-to-one correspondence of the point sets using the least square method was obtained to ensure a minimum average distance after point set registration.
b. Precision registration steps: based on the rough registration, users could interactively draw a series of feature circles on the preoperative CBCT. The algorithm would pick up the surface point set within the circle and register the preoperative surface point set and postoperative CBCT feature surface point set using an iterative closest point (ICP) registration method to obtain more accurate mapping.
c. Accuracy measurement: after overlapping of the preoperative and postoperative CBCTs, the postoperative CBCT threshold was adjusted to expose the complete image of the implant, allowing identification of the planned and actual implants and automatic calculation of the deviation between them (Wei, Li, et al., 2022).

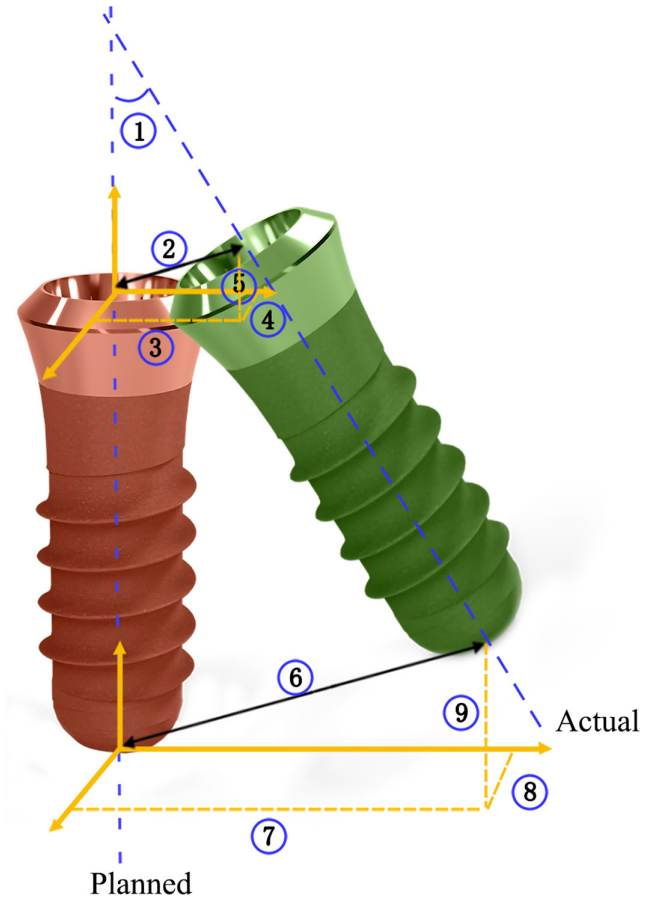

FIGURE 4 Deviations between the preoperative (planned, red implant) and postoperative (actual, green implant) implant positions. ① Angular deviation; at implant platform: ② 3D; ③ mesiodistal; ④ buccolingual; ⑤ apicocoronal; at the implant apex: ⑥ 3D; ⑦ mesiodistal; ⑧ buccolingual; ⑨ apicocoronal.

TABLE 1 Basic characteristics of the patients and implants included in the study.

Group	U-shaped tube group	Two-in-one group	*p*-value
No. patients	31	27	
Age (years)			
Mean ± SD	44.5 ± 12.6	40.2 ± 10.6	.172[a]
Range	25–68	25–64	
Gender			
Male	10 (32.3%)	5 (18.5%)	.368[b]
Female	21 (67.7%)	22 (81.5%)	
No. of implants	31	27	
Implant position			
Premolar	11 (35.5%)	6 (22.2%)	.387[b]
Molar	20 (64.5%)	21 (77.8%)	
Left side	12 (38.7%)	12 (44.4%)	.790[b]
Right side	19 (61.3%)	15 (55.6%)	
Maxilla	10 (32.3%)	5 (18.5%)	.368[b]
Mandible	21 (67.7%)	22 (81.5%)	
Implant type			
Bone level tapered	2 (6.5%)	0 (0)	.287[b]
Tissue level (Standard)	1 (3.2%)	3 (11.1%)	
Tissue level (Standard Plus)	28 (90.3%)	24 (88.9%)	
Implant diameter (mm)			
4.1	22 (71%)	16 (59.3%)	.413[b]
4.8	9 (29%)	11 (40.7%)	
Implant length (mm)			
6	0 (0)	1 (3.7%)	.267[b]
8	3 (9.7%)	4 (14.8%)	
10	19 (61.3%)	19 (70.4%)	
12	9 (29%)	3 (11.1%)	
Simultaneous bone augmentation			
Yes	7 (22.6%)	8 (29.6%)	.564[b]
No	24 (77.4%)	19 (70.4%)	

[a] Independent sample *t*-test.
[b] Fisher's exact test.

TABLE 2 Absolute values of deviation measures conforming to normal distribution.

Deviation measures	All implants	Two-in-one		U-shaped tube		p value	Mean difference	95% confidence interval of the difference	
		Mean ± SD	Range	Mean ± SD	Range			Lower	Upper
Angular deviation (°)	2.54 ± 1.21	2.21 ± 1.19	0.22–4.57	2.82 ± 1.17	0.55–5.43	.054	−0.61	−1.23	0.01
3D deviation at implant platform (mm)	0.90 ± 0.46	0.91 ± 0.45	0.15–2.09	0.89 ± 0.48	0.12–1.90	.908	0.01	−0.23	0.26
3D deviation at implant apex (mm)	1.04 ± 0.47	1.11 ± 0.46	0.44–2.09	0.99 ± 0.48	0.13–2.14	.341	0.12	−0.13	0.37

Note: Independent sample *t*-test.

2.6 | Sample size calculations

The sample size of this retrospective study was calculated using PASS software (version 22.0.2). Sample size calculations were made using a non-inferior design approach, with implant accuracy, including both platform and apex deviations, as the primary indicator of efficacy. Calculations were made on previously published preliminary results of two-in-one and U-shaped tube groups in the platform or apex deviation (Wei, Shi, et al., 2022; Wu & Sun, 2022; 0.86 ± 0.26 mm vs. 0.87 ± 0.35 mm, 0.91 ± 0.26 mm vs. 0.81 ± 0.34 mm), with clinically significant differences in the platform or apex deviation being defined by a threshold of 0.31 and 0.49 mm. At a significance level of 0.025 and power of 80%, the calculated numbers of implants required per group were 16 and 11. As such, the minimum sample size for this study was 16. In total, 27 and 31 implants were ultimately included in the two-in-one and U-shaped groups, respectively.

2.7 | Statistical analysis

Data were analyzed using SPSS 24.0 (IBM). Data distributions were analyzed with the Shapiro–Wilk test, Mann–Whitney tests, and independent sample *t*-tests being used to compare non-normally and normally distributed data, respectively. Fisher's exact test was used for comparisons of differences in deviation distributions between the U-shaped tube and two-in-one groups. $p < .05$ was the significance threshold.

3 | RESULTS

From October 2019 to August 2021, a dynamic navigation system-based approach was used to place 161 implants in posterior mandibular or maxillary sites in 116 patients in the First Clinical Division of Peking University Hospital of Stomatology. In accordance with the defined criteria for inclusion in this study, 58 of these patients (43 female, 15 male; average age: 42.5 ± 11.8 years, range: 25–68) in whom 58 implants had been placed were enrolled in this analysis. These included 31 and 27 implants in the U-shaped tube and two-in-one groups, respectively. A 100% implant success rate was achieved in the overall study cohort, and no biological or mechanical complications were reported within 1-year postimplantation in any patients. Patient demographic and clinical findings are compiled in Table 1. There were no significant differences between these two groups with respect to age, gender, implant type, implant length, implant diameter, implant position, or simultaneous bone augmentation.

In the overall patient cohort in this study, the average angular deviation was 2.54 ± 1.21°, while the respective average 3D deviation values at the implant platform and implant apex were 0.90 ± 0.46 mm and 1.04 ± 0.47 mm, respectively. The two-in-one and U-shaped tube groups showed 3D deviations at implant platform deviations of 0.91 ± 0.45 mm and 0.89 ± 0.48 mm, respectively ($p > .05$). The

mean difference was 0.01 mm between the groups, with a 95% confidence interval [−0.23, 0.26], suggesting that the lower boundary was smaller than the planned margin of 0.31 mm. Both the two-in-one and U-shaped tube groups showed 3D deviations at the implant apex deviations of 1.11 ± 0.46 mm and 0.99 ± 0.48 mm, respectively ($p > .05$). The mean difference was 0.12 mm between the groups, with a 95% confidence interval [−0.13, 0.37], suggesting that the lower boundary was smaller than the planned margin of 0.49 mm. The respective angular deviation values in the two-in-one and U-shaped tube groups were 2.21 ± 1.19° and 2.82 ± 1.17°, respectively ($p > .05$; Table 2, Figure 5).

No significant differences were detected between these two registration groups when assessing the absolute buccolingual, mesiodistal, or apicocoronal deviations at the implant platform or apex ($p > .05$; Table 3, Figure 6). Similarly, no significant differences were detected when comparing implant deviation distributions in the

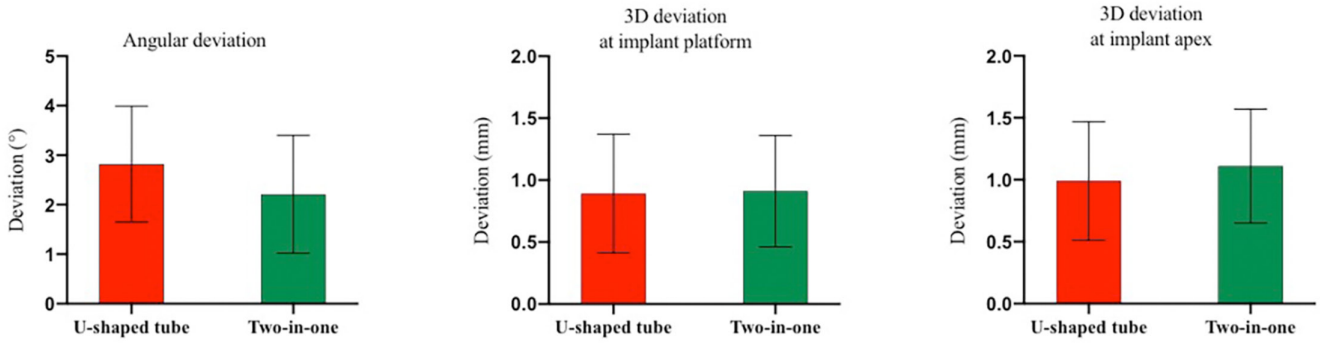

FIGURE 5 Histogram of the absolute values of deviation measures conforming to normal distribution.

TABLE 3 Absolute values of deviation measures not conforming to normal distribution.

Deviation measures		Group	Median	Q_1	Q_3	Min	Max	*p*-value
Platform (mm)	Buccolingual	U-shaped tube	0.30	0.13	0.69	0.00	1.60	.089
		Two-in-one	0.21	0.04	0.41	0.00	1.90	
	Mesiodistal	U-shaped tube	0.26	0.10	0.56	0.03	1.64	.450
		Two-in-one	0.32	0.15	0.59	0.02	1.54	
	Apicocoronal	U-shaped tube	0.33	0.15	0.69	0.02	1.33	.304
		Two-in-one	0.52	0.27	0.83	0.00	1.78	
Apex (mm)	Buccolingual	U-shaped tube	0.38	0.14	0.69	0.00	1.65	.469
		Two-in-one	0.33	0.14	0.51	0.04	1.90	
	Mesiodistal	U-shaped tube	0.53	0.25	0.84	0.03	1.96	.703
		Two-in-one	0.51	0.31	0.94	0.03	1.99	
	Apicocoronal	U-shaped tube	0.34	0.17	0.66	0.03	1.26	.215
		Two-in-one	0.51	0.27	0.84	0.01	1.78	

Note: Mann–Whitney U test.

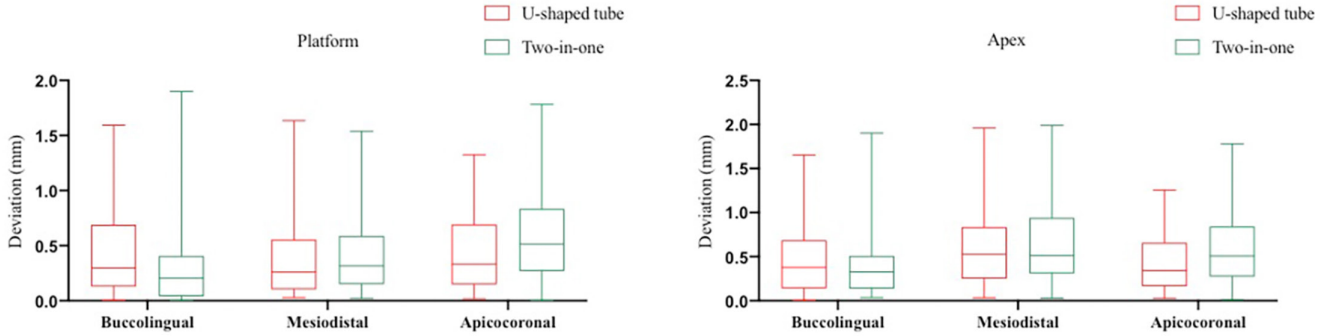

FIGURE 6 Box plots of absolute values of deviation measures not conforming to normal distribution (error bars represent the extremum, the bottom and top edges represent the Q_1 and Q_3, within the box, and a line represents the median).

TABLE 4 Distribution differences of deviation direction between U-shaped tube and two-in-one groups.

Position	Group	Total	Buccal	Lingual	*p* value	Mesial	Distal	*p* value	Coronal	Apical	*p*-value
Platform	U-shaped tube	31	22	9	1.000	16	15	.293	18	13	.791
	Two-in-one	27	19	8		18	9		17	10	
Apex	U-shaped tube	31	19	12	.292	15	16	.062	17	14	.795
	Two-in-one	27	12	15		20	7		16	11	

Note: Fisher's exact test.

apical, coronal, lingual, buccal, mesial, or distal directions ($p > .05$; Table 4). A scatter plot showing the deviations of all 58 implants in each direction is provided in Figure 7.

4 | DISCUSSION

The use of dCAIS systems when performing dental implant surgery has been commonplace for roughly two decades (Ewers et al., 2004; Siessegger et al., 2001), with both sCAIS and dCAIS strategies aiding in more accurate and optimal implant placement relative to free-hand surgical approaches (De Souza et al., 2022; Kaewsiri et al., 2019; Stefanelli et al., 2019; Sun et al., 2022; Vercruyssen et al., 2014; Wang et al., 2021; Yimarj et al., 2020). Recent rapid advances in navigational technologies have led to the publication of many studies on this topic in recent years, with a pooled implant loss rate of just 1% having been reported among 10 studies assessing the complications and failure rates associated with 1039 implants (Pellegrino et al., 2021).

Jorba-García et al. recently conducted a systematic assessment of the relative accuracy of dCAIS procedures in published clinical studies (Jorba-García et al., 2021), reporting average angular deviation, coronal global deviation, and apical global deviation values of 3.68°, 1.03 mm, and 1.34 mm, respectively. When assessing 231 implants in 89 arches, Stefanelli et al. (2019) measured average angular deviation, apex deviation, and entry point (lateral) deviation values of 2.26 ± 1.62°, 1.00 ± 0.49 mm, and 0.71 ± 0.40 mm, respectively. Block, Emery, Cullum, et al. (2017) examined accuracy metrics associated with the use of a fully guided dynamic navigation implant placement strategy, reporting mean angular deviation, global apical deviation, and global platform deviation values of 2.97 ± 2.09°, 1.29 ± 0.65 mm, and 1.16 ± 0.59 mm, respectively. In a separate analysis focused on the dynamic navigation-based placement of posterior maxillary implants, Aydemir and Arısan observed respective average angular, apical, and coronal deviation values of 5.59 ± 0.39°, 1.83 ± 0.12 mm, and 1.01 ± 0.07 mm, respectively (Aydemir & Arısan, 2020). Overall, these findings suggest that the average angular deviation values generally range from 2 to 5.6°, whereas the average global platform deviation is ~1 mm and the average global apex deviation is 1–1.8 mm. In the present overall study cohort of patients undergoing dynamic navigation-based implant placement in maxillary or mandibular sites missing a single tooth, the respective average angular, platform, and apex deviation values were 2.54 ± 1.21°, 0.90 ± 0.46 mm, and 1.04 ± 0.47, respectively, in line with these past results.

No significant differences were observed between the two-in-one and U-shaped tube groups when assessing absolute buccolingual, mesiodistal, and apicocoronal deviation values at the implant platform or apex. Similarly, implant deviation distributions in these groups were comparable in the apical, coronal, mesial, distal, lingual, and buccal directions. In their prior in vitro analysis, Pei et al. (2022) observed lingual deviation for 85% of implants, whereas Yimarj et al. (2020) observed more significant lingual deviation at the implant platform and more significant distal deviation at the apex for dCAIS relative to sCAIS. Moreover, Kaewsiri et al. (2019) detected more mesial deviation at the platform level in the dCAIS group relative to the sCAIS group. These variations among studies may be attributable to the experience levels of the operating surgeon, the surgeon's field of view or positioning given the reliance of dCAIS on direct visualization and a manual approach, and the utilized registration method and registration points given that when these are not appropriately selected it can contribute to dCAIS deviation and drift.

Postoperative accuracy can be impacted by the proficiency of surgeons utilizing a dynamic navigation approach, with implant placement being easier for anterior sites relative to posterior sites (Golob Deeb et al., 2019). Effectively utilizing dynamic navigation relies on the acquisition of appropriate hand–eye coordination during the surgical process and can entail a substantial learning curve (Block, Emery, Lank, et al., 2017; Stefanelli et al., 2019). All implant procedures in this study were performed by two surgeons with over 10 years of experience performing conventional implant surgery and over 4 years of experience utilizing a dCAIS system.

The accuracy of a dCAIS system can be impacted by many different factors, such as the quality of CBCT images as a result of the acquisition or processing of these data, the overall calibration and registration procedure, target registration errors from the tracking system, or various forms of human error during the preoperative, intraoperative, or postoperative phases (Jorba-García et al., 2021; Widmann & Bale, 2006). Given the importance of selecting an appropriate registration method, this was the focus of the present study. As the U-shaped tube-based registration technique is manual and relies on 6 registration points and an active infrared signal, it requires 4–5 min to complete the intraoral positioning. In contrast, the two-in-one technique requires just three registration points and utilizes both passive and active infrared signals such that extraoral positioning can be completed in 10–20 s. For further comparisons of these two registration techniques, see Table 5.

Based on our experience, we believe that taking several factors into consideration can ensure optimal accuracy when using

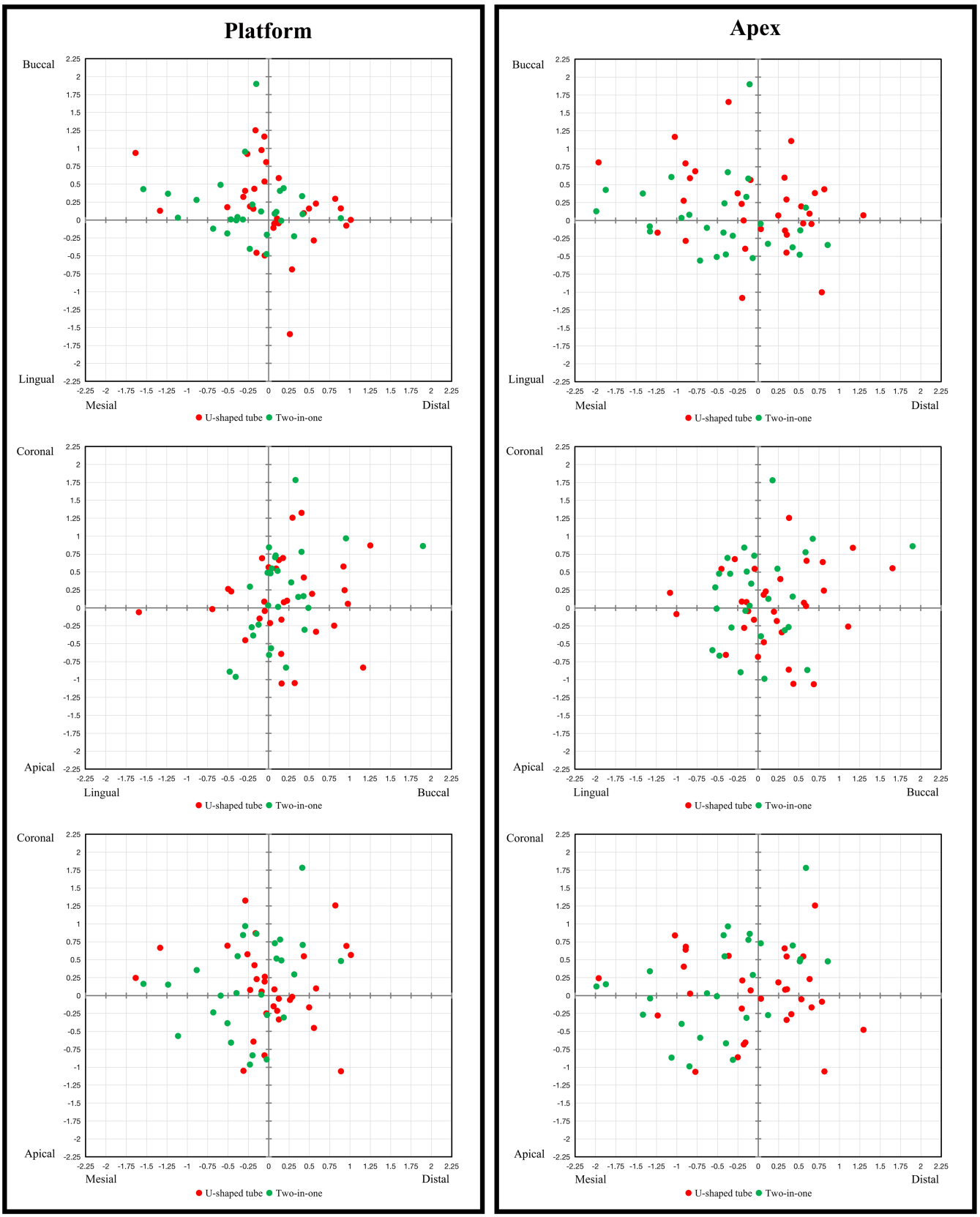

FIGURE 7 Scatter plots indicating the implant deviation at implant platform and apex in buccolingual, mesiodistal, and apicocoronal direction.

TABLE 5 Difference between U-shaped tube and two-in-one registration methods.

Group	Method	Device number	Device size	Registration points	Position	Time	Operation	Fault tolerance rate
U-shaped tube	Manual (AI)	Two	Large	Six	Intraoral	4–5 min	Complex	High
Two-in-one	Automatic (API)	One	Small	Three	Extraoral	10–20 s	Simple	Low

Note: API: active and passive infrared registration method; AI: active infrared registration method.

either of these dynamic navigation system-based registration approaches. Care must be taken when selecting the registration device type, positioning, and finishing when conducting U-shaped tube registration. In patients missing the free ends of the posterior teeth, we utilized a longer registration device and more silicone rubber to extend the device. During CBCT imaging, patients can also bite down on rolled cotton on the registration device. These strategies can lead to improvements in the stability and repeatability of registration-related manipulations. During implant placement, pressure must be steadily applied to the registration devices, and registration points must be evenly distributed to ensure that registration is appropriately completed (Bettschart et al., 2012). After registration is complete, infiltration anesthesia can be performed, especially in patients missing the free ends of posterior teeth, thereby ensuring that changes in the soft tissue do not impact the overall accuracy of the registration process. As the reflective patches employed by the two-in-one system are outside the implant area, this has the potential to lower the accuracy of the implantation procedure (Luebbers et al., 2008; Venosta et al., 2014). The device should thus be positioned as near the surgical area as possible without interfering with the procedure. For extraoral registration, the two-in-one and reference devices can be tested in several spaces to determine the optimal conformation that affords the greatest registration accuracy.

Despite the above clinical experience, most clinical risks can be avoided, although there remains the unavoidable problem of the maximum error in the dynamic navigation. In this study, the maximum 3D deviation at the implant platform was found to be 2.09 mm in the two-in-one group, while the maximum 3D deviation at the implant apex was 2.14 mm in the U-shaped tube group. Uneven density (high or low density) and irregular shape of the alveolar bone may affect the postoperative accuracy. A particular case in the two-in-one group was a 60-year-old female (tooth 46 missing) who had low bone density. It is difficult to control the direction and force of the drills when dCAIS is used. A case in the U-shaped tube group was a 67-year-old female (tooth 36 missing) with uneven bone density. The reason for the removal of tooth 36 was severe periapical periodontitis. The implant surgery was performed four months after the tooth extraction. The density of the alveolar bone was uneven, and the bone density of the root tip was low. Based on the analysis of this case, to obtain uniform bone density, we suggest that the optimal time for placing the implant would be at least 6 months after the extraction. Figures 6 and 7 clearly show that at the buccolingual and mesiodistal deviations at the implant platform position, deviations of more than 1 mm can occur. These may lead to occasionally unpredictable simultaneous bone augmentation and injury to adjacent teeth. This should be judged intraoperatively according to the clinical experience of the surgeon to prevent the occurrence of associated complications.

This study is the first to our knowledge to have compared a MR technique relying on active infrared signals to an automatic registration technique employing both active and passive infrared signaling. For this retrospective analysis, 58 patients and 58 implants were evaluated to assess the relative accuracy of these different registration strategies, ultimately revealing no significant differences between the two groups. The two-in-one group was not inferior to the U-shaped tube group in terms of 3D deviations at the implant platform and apex when the non-inferiority margins were 0.31 and 0.49 mm. U-shaped tube-based registration is highly accurate and is commonly implemented in clinical settings. However, the two-in-one system employs a simpler extraoral registration method that lowers the number and size of devices used, decreases the number of operative steps in the registration process, and reduces the surgical duration. Even so, this two-in-one approach is subject to several limitations. Notably, it cannot be used for areas exhibiting loose residual teeth, restorations, or malocclusion, generally necessitating three posterior teeth and four anterior teeth. In addition, the reflective patches that this device uses are not within the surgical area, and as a result, the distance between the registration points and the implant area has the potential to impact postoperative accuracy. Third, this device entails just three registration points and exhibits a low tolerance for faults.

While these results highlight the accuracy of both two-in-one and U-shaped tube registration strategies, this was only a retrospective analysis of a limited number of patients, highlighting a need for further large-scale prospective research. In addition, these analyses were restricted to the placement of dental implants in posterior sites missing a single tooth, and additional work will be needed to examine the relative value of these different registration strategies when multiple teeth are missing or when anterior implant surgery is being performed.

5 | CONCLUSION

In summary, the present results indicate that both the U-shaped tube and two-in-one registration devices can facilitate the accurate and reliable placement of dental implants in vivo in posterior sites missing a single tooth. It is important to note that the two-in-one

registration strategy relies on an automated, straightforward extraoral approach, thereby decreasing the size and number of devices employed, the number and complexity of steps required for intraoperative registration, and the overall operative duration relative to U-shaped tube-based registration. However, further studies comparing these systems in detail are needed.

AUTHOR CONTRIBUTIONS

Bin-Zhang Wu: design, data collection, drafting article, applied for financial support, and approval of article. Fei Xue: data analysis, statistics analysis, critical revision of article, and approval of article. Yu Ma: preoperative and intraoperative software use. Feng Sun: design, critical revision of article, and approval of article.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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ETHICS APPROVAL STATEMENT

This study was approved by the Institutional Review Board of Peking University School and Hospital of Stomatology (PKUSSIRB-202165090). All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board of Peking University School and Hospital of Stomatology and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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