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Original Article

Accuracy and efficiency of a calibration approach in dynamic navigation for implant placement: An in vitro study

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KEYWORDS
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Abstract *Background/purpose:* Computer-assisted dynamic navigation surgery could provide accurate implant placement. However, its low efficiency was always criticized by dental surgeons. The purpose of this study was to evaluate the accuracy and efficiency of a calibration approach with reflective wafers in dynamic navigation for implant placement.
Materials and methods: Eighty implants were placed in the standardized polyurethane mandibular models under dynamic navigation and divided into 2 groups according to the calibration methods ($n = 40$). The U-shaped tube (UT) group used a prefabricated U-shaped tube embedded with radiopaque markers. The reflective wafers (RW) group used a fixation with 3 round reflective wafers as markers. Postoperative cone beam computed tomography images were obtained for implants deviation analyses. The calibration time was used to evaluate the efficiency of the 2 methods.
Results: Significant differences were found in the trueness and efficiency between the 2 groups ($P < 0.05$). The 3D deviations at the implant platform and apex were smaller in UT group (0.89 ± 0.28 and 0.79 ± 0.30 mm, respectively) than in the RW group (0.99 ± 0.28 and 0.98 ± 0.30 mm, respectively). The angular deviation was larger in the UT group ($2.16 \pm 1.12°$) than in the RW group ($1.53 \pm 0.88°$). The calibration approach of RW group was more efficient than the UT group (2.05 ± 0.55 and 7.50 ± 0.71 min, respectively).

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Conclusion: The calibration method of RW improved the efficiency significantly and achieved equivalent trueness with UT for dynamic navigation during implant placement.

Introduction

The optimal position, orientation and depth of implant placement are key issues for successful implantation. Accurate implant placement could reduce the risks of immediate or long-term prosthetic and biological complications.[1–6] Computer-assisted navigation systems could achieve more accuracy than the freehand method while implant placement.[2,7–10] Navigation systems included static and dynamic navigation.[2] Dynamic navigation surgery has better visualization and cooling capacity than static navigation.[11] It was reported that dynamic navigation could reduce the 3-dimensional (3D) deviation to 0.69–0.72 mm, and the angular deviation to 3.59°.[1–4] Therefore, dynamic navigation become widely used in clinical practice, surgical teaching, and research.[12–15]

Several calibration methods could be used during dynamic navigation: U-shaped tube with embedded radiographic markers, anatomic tooth cusps markers, metal screws as bone markers, and noninvasive adhesive markers.[16–19] U-shaped tube could be suggested using in partially edentulous individuals as its better accuracy than the others.[16,20] However, the procedure of registration and calibration were complex before implantation, usually 5–8 min were consumed.[21] Anatomic tooth cusps markers could be suggested using in single missing tooth as its convenience without additional device.[22] However, when used in partially edentulous arch, the accuracy was not enough. Metal screws as bone markers were suggested using for edentulous arch, of which the shortcomings were the invasion into bone traumatically.[23] Noninvasive adhesive markers was 3D printed and used mainly in edentulous arch.[18]

Recently, a calibration method was introduced using an acrylic resin fixation with 3 round reflective wafers (RW).[21] The 3 markers of RW could be calibrated at the same time, while using U-shaped tube the 6 embedded markers should be calibrated one by one. Thus, the RW method might save clinical time. However, it was unclear if the RW calibration approach could achieve the equivalence trueness compared with the U-shaped tube method in the distal extension of partially edentulous arch. In addition, there were a trend that the deviation of the posterior teeth was higher than the anterior teeth.[3] However, there was no evidence to verify if molars deviation were higher than premolars in the distal extension arch.

The primary purpose of this in vitro study was to compare the trueness and efficiency of 2 different calibration methods of dynamic navigation while dental implantation in the distal extension of partially edentulous arch. The secondary purpose was to explore if there was different trueness between premolars and molars. The null hypothesis was that no difference would be found in the trueness and efficiency of the 2 calibration methods used for the dynamic navigation systems, and no difference would be found in the trueness of premolars and molars.

Materials and methods

This study was performed in accordance with the checklist for reporting in vitro studies (CRIS) guidelines. The study was carried out on standardized polyurea-thane mandibular models with distal extensions of a partially edentulous arch. In total, 80 implants were divided into 2 groups based on the calibration methods used in the study: the U-shaped tube (UT) group used a prefabricated U-shaped tube embedded with radiopaque markers (Yizhimei, Digital health care, Suzhou, China) (Fig. 1); the RW group used the acrylic resin fixation with 3 round RW (Yizhimei, Digital health care) as markers (Fig. 2).[21]

Before implant placement, the models in the UT group were tagged with prefabricated acrylic resin U-shaped tube with several Ø1.0-mm metal radiographic markers as previously published study (Fig. 1A).[16] In RW group, the models were tagged with an acrylic resin fixation with 3 round reflective and radiopaque wafers (Fig. 2A). The Ø3.0-mm wafers as markers allowed visualization of the 3D orientation of the model with cone beam computed tomography (CBCT). The CBCT (CS9300, Carestream Health, Rochester, NY, United States) scans were performed under uniform conditions (60 kV, 3.2 mA, 8 s), and the data were copied into a dynamic navigation system (Yizhimei, Digital health care) to plan virtual implant placement, including position and orientation. All implants were Ø4.1 × 10 mm (Bone level implant, Institut Straumann AG, Basel, Swiss).

When implant placement, the spatial positions of the model with markers and handpiece with tracking points were continuously tracked by the stereoscopic camera of the dynamic navigation system. In the UT group, the handpiece was traditional one and there were no gears (Fig. 1B). Six metal markers embedded in the prefabricated U-shaped tube were used for calibration, and this approach would take several minutes (Fig. 1C). In the RW group, the special handpiece with 5 gears was registered by the tracking points (Fig. 2B). The gear number should be the same with the number in the software (Fig. 2C). The spatial model was calibrated to the preoperative virtual design through CBCT by the 3 reflective wafers in the fixation (Fig. 2D). The registration time of handpiece and calibration time of the model in the 2 groups were recorded to evaluate the efficiency.

During implant placement, real-time video on a laptop screen was used to guide implant position, orientation, and depth (Fig. 1D). A hole was drilled in the model for implant placement with a handpiece in real time. Dynamic

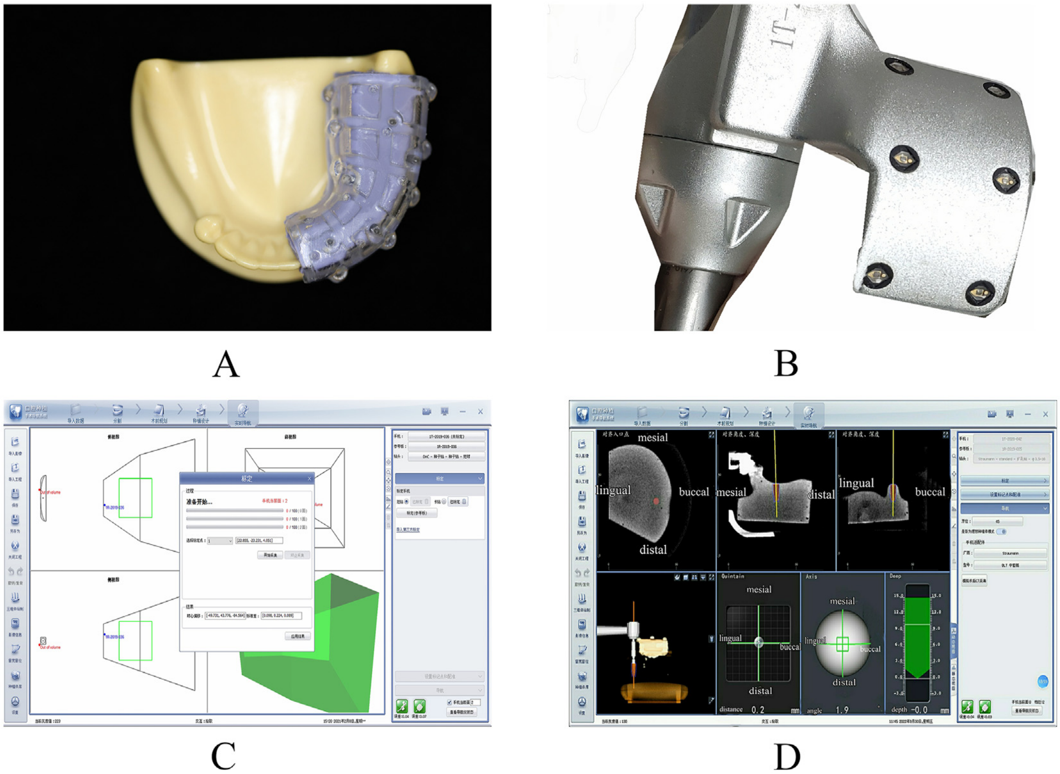

Figure 1 Implants placement using the dynamic navigation with a calibration approach of U-shaped tube. (A) Model tagged with U-shaped tube embedded with radiographic markers; (B) Traditional handpiece without gears; (C) Registration needed several minutes with 3 times of recognition; (D) During drilling procedure and implant placement, real time video could show the position, orientation, and depth. The color would turn red if deviation was beyond the threshold, otherwise, the color should be green.

deviation was continuously monitored and displayed in red color (instead of the standard green color) if the deviation reached the threshold value. The implants were placed in real time by a single experienced right-handed surgeon.

After implant placement, the models were scanned using CBCT (CS9300, Carestream Health) performed under the same conditions as the pre-implant CBCT. The preoperative and postoperative CBCT images were compared using the radiographic markers included in the implant accuracy analysis system (Implant Precision Systems, Digital health care). Accuracy consists of trueness and precision. Trueness is determined as the difference between the actual and planned positions, while precision is defined by the consistency between multiple measurements. The planned and actual implant parameters were compared to determine the 3D deviations of trueness at the implant platform and apex, angular deviations, horizontal and depth deviations at the implant platform and apex (Fig. 3). The measurements were obtained by a single blinded examiner who was not involved in the study design.

The data were analyzed with a statistical software program (IBM SPSS Statistics, v22.0, IBM Corp, Armonk, NY, United States). Quantitative data are expressed as mean $\pm$ standard deviation (SD). Trueness and efficiency differences between the 2 groups were analyzed by using T test. Two-way multivariate analysis of variance (MANOVA) was used to determine whether there was a difference in trueness values in accordance with the interaction between the type of calibration methods and tooth site ($\alpha = 0.05$).

Results

Significant differences were found in the trueness and efficiency between the 2 groups ($P < 0.05$). The 3D deviations and angular deviation in 2 calibration groups are shown in Table 1. The 3D deviations at the implant platform and apex were smaller in UT group (0.89 $\pm$ 0.28 and 0.79 $\pm$ 0.30 mm, respectively) than in the RW group (0.99 $\pm$ 0.28 and 0.98 $\pm$ 0.30 mm, respectively). The UT group had a higher trueness than the RW group for 3D deviation ($P < 0.05$). The angular deviation was larger in the UT group (2.16 $\pm$ 1.12°) than in the RW group (1.53 $\pm$ 0.88°). The RW group had a higher trueness of angulation than the UT group ($P = 0.005$).

The horizontal and depth deviations at implant platform and apex are shown in Table 2. There was no significant differences of horizontal deviation at implant platform ($P = 0.052$) and apex ($P = 0.177$) between the groups. With regard to depth deviation, the UT group resulted deeper placement and the RW group resulted shallower placement ($P < 0.001$). However, the absolute values were similar between the 2 groups regardless of the direction of depth deviation.

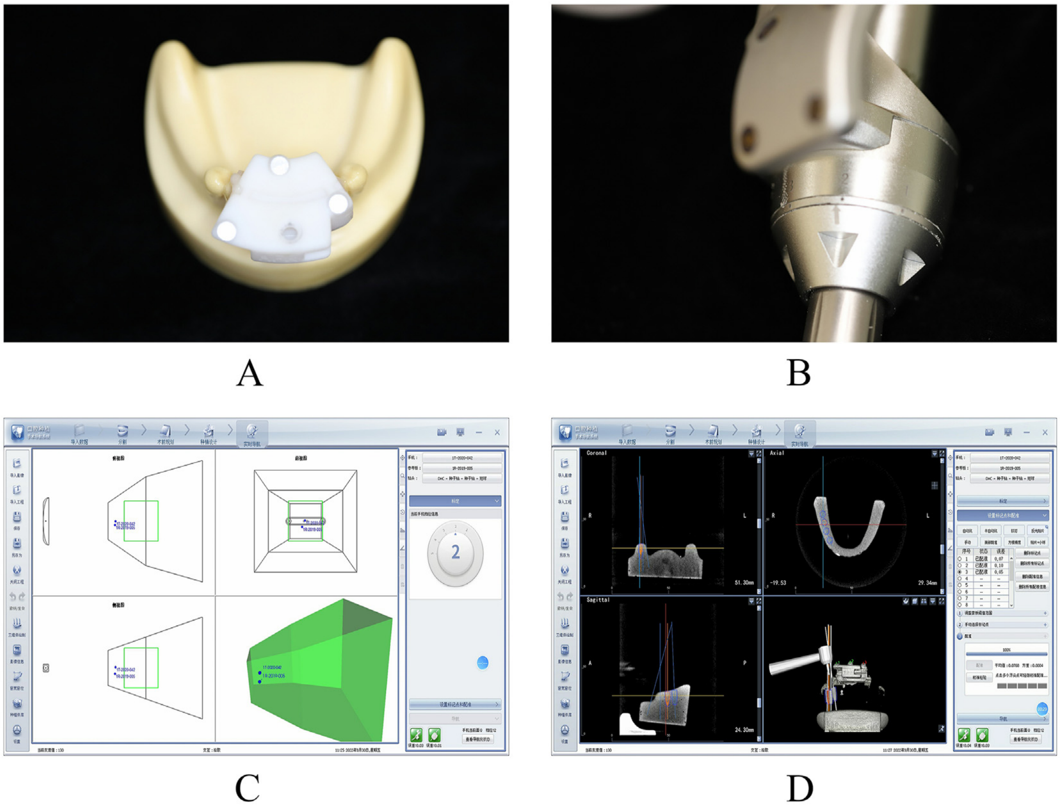

Figure 2 The calibration approach of fixation with 3 reflective wafers for dynamic navigation aided implant placement in distal extension models. (A) Model tagged with fixation with 3 round reflective wafers as markers; (B) Special handpiece with 5 gears was registered by the tracking points; (C) Registration of handpiece was done by matching the gear number; (D) Calibration was done by the 3 reflective wafers in the fixation.

The accuracy between calibration approach and tooth site are shown in Tables 3–5. With regard to 3D deviation at the implant apex, the molars had lower trueness (1.00 ± 0.29 mm) than the premolars (0.77 ± 0.29 mm) ($P < 0.001$). There was no significant difference between premolars and molars in terms of trueness according to the 3D deviation at the implant platform, angular deviation, horizontal and depth deviations (all $P > 0.05$) (Table 5).

The mean times of handpiece registration and model calibration were 7.50 ± 0.71 min in the UT group and 2.05 ± 0.55 min in the RW groups (Fig. 4). The calibration approach of RW was more efficient than that for UT ($P < 0.001$).

Discussion

The in vitro study on dental models compared the accuracy of 2 calibration approaches of dynamic navigation for dental implant placement in the distal extension of partially edentulous arch. The dynamic navigation could achieve high trueness in both RW and UT groups. Further, UT group had a higher trueness in 3D location, while RW group had a higher trueness as for angulation. The RW group was more efficient than the UT group. Meanwhile, there was limited significant trueness difference between the premolars and molars.

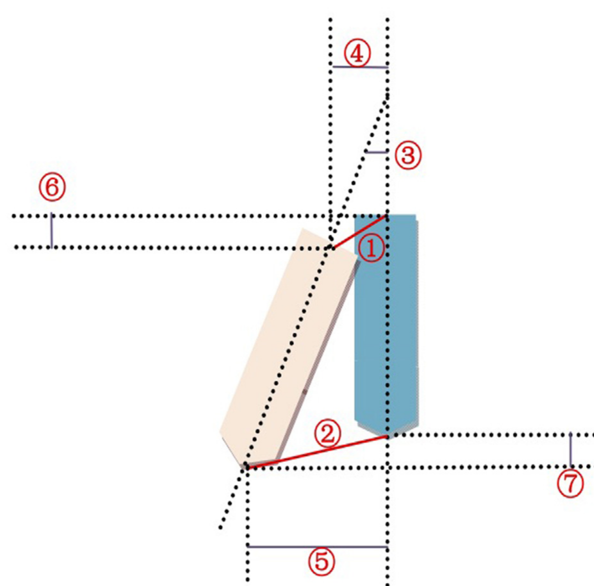

Figure 3 Illustration of parameters indicating implant deviations. Purple color indicates planned virtual implant and orange color indicates placed implant. ① Three-dimensional (3D) deviation at implant platform; ② 3D deviation at implant apex; ③ Angular deviation; ④ Horizontal deviation at implant platform; ⑤ Horizontal deviation at implant apex; ⑥ Depth deviation at implant platform; ⑦ Depth deviation at implant apex.

Table 1 Mean ± standard deviation of 3-dimensional (3D) deviations (mm) and angular deviation (degrees) in 2 calibration groups.

Groups	3D deviation at implant platform	3D deviation at implant apex	Angular deviation
U-shaped tube group (n = 40)	0.89 ± 0.28	0.79 ± 0.30	2.16 ± 1.12
Reflective wafers group (n = 40)	0.99 ± 0.28	0.98 ± 0.30	1.53 ± 0.88
t value	−1.59	−2.80	2.78
P value	0.013[a]	0.004[a]	0.005[a]

[a] Statistical significance by T test between U-shaped tube group and reflective wafers group ($P < 0.05$).

Table 2 Mean ± standard deviation of horizontal and depth deviations (mm) at implant platform and apex of 2 calibration groups.

Groups	Horizontal deviation at implant platform	Horizontal deviation at implant apex	Depth deviation at implant platform	Depth deviation at implant apex
U-shaped tube group (n = 40)	0.77 ± 0.32	0.65 ± 0.35	0.22 ± 0.35	0.23 ± 0.35
Reflective wafers group (n = 40)	0.74 ± 0.32	0.74 ± 0.38	−0.31 ± 0.51	−0.22 ± 0.57
t value	0.40	−1.07	5.49	4.34
P value	0.052	0.177	<0.001[a]	<0.001[a]

[a] Statistical significance by T test between U-shaped tube group and reflective wafers group ($P < 0.05$).

Table 3 Mean ± standard deviation of 3-dimensional (3D) deviations (mm) and angular deviation (degrees) at different tooth sites.

Groups	Tooth sites	3D deviation at implant platform	3D deviation at implant apex	Angular deviation
U-shaped tube group	Molar (n = 20)	0.93 ± 0.33	0.92 ± 0.27	2.02 ± 1.04
	Premolar (n = 20)	0.85 ± 0.22	0.67 ± 0.28	2.30 ± 1.22
Reflective wafers group	Molar (n = 20)	1.07 ± 0.27	1.09 ± 0.29	1.48 ± 0.81
	Premolar (n = 20)	0.91 ± 0.27	0.87 ± 0.27	1.58 ± 0.96
Total	Molar (n = 40)	1.00 ± 0.31	1.00 ± 0.29	1.75 ± 0.96
	Premolar (n = 40)	0.88 ± 0.24	0.77 ± 0.29	1.94 ± 1.14

Table 4 Mean ± standard deviation of horizontal and depth deviations (mm) at implant platform and apex at different tooth sites.

Groups	Tooth sites	Horizontal deviation at implant platform	Horizontal deviation at implant apex	Depth deviation at implant platform	Depth deviation at implant apex
U-shaped tube group	Molar (n = 20)	0.75 ± 0.38	0.71 ± 0.36	0.25 ± 0.46	0.26 ± 0.46
	Premolar (n = 20)	0.79 ± 0.26	0.58 ± 0.33	0.20 ± 0.19	0.21 ± 0.19
Reflective wafers group	Molar (n = 20)	0.78 ± 0.38	0.81 ± 0.40	−0.43 ± 0.54	−0.25 ± 0.63
	Premolar (n = 20)	0.70 ± 0.38	0.66 ± 0.36	−0.20 ± 0.47	−0.19 ± 0.48
Total	Molar (n = 40)	0.77 ± 0.38	0.76 ± 0.38	−0.91 ± 0.60	0.01 ± 0.60
	Premolar (n = 40)	0.75 ± 0.33	0.62 ± 0.34	0.01 ± 0.41	0.01 ± 0.41

With regard to the trueness, both the UT and RW groups had their pros and cons. RW had a higher trueness in angulation, while UT had better results in 3D location. The accuracy results were as good as previous study.[16,21,22,24] However, RW has less time consumption (2.05 ± 0.55 min) on the registration and calibration procedure than the UT group (7.50 ± 0.71 min) before implant placement. At this aspect, RW had wonderful advantage than UT to save time for implant placement preparation. Therefore, RW method could be suggested using in partially distal extension arch with the advantage of high trueness and low time consume.

The evaluation of precision targets random errors and the precise implant placement was quite important to

Table 5 Results of 2-way MANOVA test for accuracy between calibration method and tooth site.

Accuracy	Source	Type III sum of squares	df	Mean squares	*F* value	*P* value
3D deviation at implant platform	Calibration method	0.198	1	0.198	2.605	0.111
	Tooth site	0.265	1	0.265	3.499	0.065
	Calibration method × tooth site	0.463	2	0.231	3.052	0.053
3D deviation at implant apex	Calibration method	0.695	1	0.695	9.285	0.003[a]
	Tooth site	1.071	1	1.071	14.140	<0.001[a]
	Calibration method × tooth site	1.766	2	0.883	11.662	<0.001[a]
Angular deviation	Calibration method	7.894	1	7.894	7.720	0.007[a]
	Tooth site	0.682	1	0.682	0.667	0.417
	Calibration method × tooth site	8.576	2	4.288	4.194	0.019[a]
Horizontal deviation at implant platform	Calibration method	0.020	1	0.020	0.158	0.692
	Tooth site	0.007	1	0.007	0.059	0.809
	Calibration method × tooth site	0.027	2	0.014	0.109	0.897
Horizontal deviation at implant apex	Calibration method	0.152	1	0.152	1.171	0.282
	Tooth site	0.402	1	0.402	3.101	0.082
	Calibration method × tooth site	0.554	2	0.277	2.136	0.125
Depth deviation at implant platform	Calibration method	5.806	1	5.806	30.096	<0.001[a]
	Tooth site	0.169	1	0.169	0.876	0.352
	Calibration method × tooth site	5.975	2	2.987	15.486	<0.001[a]
Depth deviation at implant apex	Calibration method	4.066	1	4.066	18.552	<0.001[a]
	Tooth site	0.001	1	0.001	0.004	0.952
	Calibration method × tooth site	4.067	2	2.033	9.278	<0.001[a]

3D, three-dimensional.
[a] Statistical significance by MANOVA test between 2 calibration methods or 2 tooth sites ($P < 0.05$).

prevent anatomical structure damage. Error in the radiographic acquisition, virtual planning and actual operation could accumulate, thus quality control of each step could maximize the final accuracy. A previous study reported that the angular errors could achieve 11.94° and the 3D deviation at the apex could achieve 4.55 mm.[1] In the present research, the UT group had equivalent precision (standard deviation) of 3D deviation and lower precision (larger standard deviation) of angular deviation than the RW group. Therefore, although dynamic navigation could increase the trueness of implant placement, the accuracy varies with the experience and eye-hand coordination skills of the operators. That means surgeons are suggested not to fully rely on dynamic navigation systems. Before performing on patients, surgeons should practice dynamic navigation on in vitro models to reduce errors in clinical practice.[5,24]

Premolars groups had a higher trueness than the molars groups as for the 3D deviations at implant apex. The further from the neighboring natural teeth, the lower accuracy could be achieved. There were limited evidence to support this point in the literatures.[1,25] In a study on the full edentulous mandibular model, although no significant difference was seen between the anterior and posterior teeth, there were still a trend that the deviation of the posterior teeth was higher than the anterior teeth.[3] In real world clinical surgery, the more posterior teeth, the worse vision achieved as the limited mouth opening. Even though dynamic navigation could aid implant placement to some extent, surgeons should pay more attention on location and angulation at the molars, especially at the second molars.

The present in vitro study has some limitations. Although standardized models provide uniform conditions to minimize sampling error, navigation accuracy may differ between models and patients because of patient movement, mouth opening, restricted visualization, and the effects of blood and saliva. Clinical trials are needed to validate the present results. However, the study can be helpful for clinicians to choose the more efficient and accurate

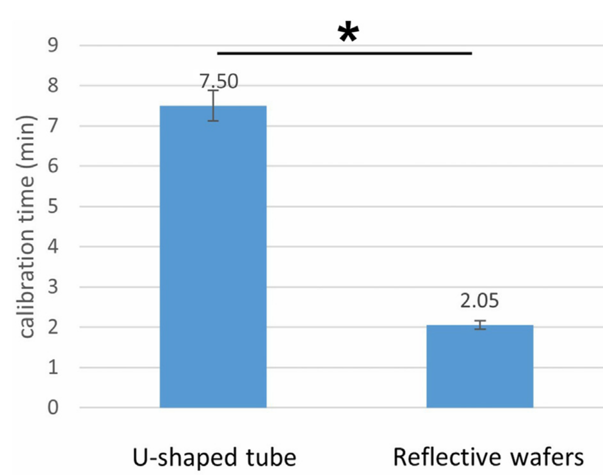

Figure 4 The registration time of handpiece and calibration time of the models in the 2 groups. * The calibration approach of RW was more efficient than that of UT significantly ($P < 0.001$).

calibration method for implant placement while using dynamic navigation.

Based on the findings of this in vitro study, the following conclusions were drawn: The use of RW resulted in more efficient registration and calibration procedures compared to the use of UT. The dynamic navigation achieved equivalent trueness between RW and UT for implant placement at the distal extension of partially edentulous arches.

Declaration of competing interest

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

Acknowledgments

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