Journal of Dental Sciences 19 (2024) 196–202

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.e-jds.com

Original Article

Comparison of the accuracy of dental implant placement using dynamic and augmented reality-based dynamic navigation: An *in vitro* study

Baoxin Tao [a,b†], Xingqi Fan [c†], Feng Wang [a,b], Xiaojun Chen [c*], Yihan Shen [a,b**], Yiqun Wu [a,b*]**

[a] *Department of Second Dental Center, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, College of Stomatology, Shanghai Jiao Tong University, Shanghai, China*
[b] *National Center for Stomatology, National Clinical Research Center for Oral Diseases, Shanghai Key Laboratory of Stomatology, Shanghai Research Institute of Stomatology, Shanghai, China*
[c] *Institute of Biomedical Manufacturing and Life Quality Engineering, State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China*

Received 21 April 2023; Final revision received 5 May 2023
Available online 16 May 2023

KEYWORDS
Surgery;
Computer-assisted;
Augmented reality;
Dental implants

Abstract *Background/purpose:* Augmented reality has been gradually applied in dental implant surgery. However, whether the dynamic navigation system integrated with augmented reality technology will further improve the accuracy is still unknown. The purpose of this study is to investigate the accuracy of dental implant placement using dynamic navigation and augmented reality-based dynamic navigation systems.
Materials and methods: Thirty-two cone-beam CT (CBCT) scans from clinical patients were collected and used to generate 64 phantoms that were allocated to the augmented reality-based dynamic navigation (ARDN) group or the conventional dynamic navigation (DN) group. The primary outcomes were global coronal, apical and angular deviations, and they were measured after image fusion. A linear mixed model with a random intercept was used. A *P* value < 0.05 was considered to indicate statistical significance.

* Corresponding author. Department of Second Dental Center, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, 280 Mohe Road, Shanghai, 201999, China.
** Corresponding author. Department of Second Dental Center, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, 280 Mohe Road, Shanghai, 201999, China.
*** Corresponding author. School of Mechanical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai, 200240, China.
E-mail addresses: xiaojunchen@sjtu.edu.cn (X. Chen), 1413313536@qq.com (Y. Shen), yiqunwu@hotmail.com (Y. Wu).
† Both authors have contributed equally to this work.

https://doi.org/10.1016/j.jds.2023.05.006

Results: A total of 242 dental implants were placed in two groups. The global coronal, apical and angular deviations of the ARDN and DN groups were 1.31 $\pm$ 0.67 mm vs. 1.18 $\pm$ 0.59 mm, 1.36 $\pm$ 0.67 mm vs. 1.39 $\pm$ 0.55 mm, and 3.72 $\pm$ 2.13° vs. 3.1 $\pm$ 1.56°, respectively. No significant differences were found with regard to coronal and apical deviations ($P = 0.16$ and 0.6, respectively), but the DN group had a significantly lower angular deviation than the ARDN group ($P = 0.02$).
Conclusion: The augmented reality-based dynamic navigation system yielded a similar accuracy to the conventional dynamic navigation system for dental implant placement in coronal and apical points, but the augmented reality-based dynamic navigation system yielded a higher angular deviation.

Introduction

Because proper three-dimensional (3D) positioning of dental implants ensures promising prosthetic and aesthetic outcomes, the accurate reproduction of the planned virtual implant in a real surgical environment is essential.[1] To guarantee the accuracy of reproduction, computer-assisted implant surgery (CAIS) has been introduced,[2] which can provide more accurate dental implant placement than free-hand surgery.[3–5] CAIS can be classified into static and dynamic systems according to guiding principles. Static CAIS (sCAIS) has been widely applied in clinical practice and uses a prefabricated surgical guide to restrict the position and direction of drills according to preoperative plans. According to a recent systematic review, sCAIS yielded a high accuracy with entry, exit and angle deviations of 1.03 mm, 1.33 mm and 2.68°, respectively.[6] However, the accuracy of sCAIS may decrease when patients have limited mouth opening or poorly supported tissues.[7,8] The static guide cannot offer constant visualization and obtain real-time feedback on the relationship between drills and planned paths.[9] Therefore, dynamic navigation is introduced in dental implant surgery to overcome these limitations.

A dynamic navigation system can track the movements of the patient and surgical instruments.[10] Therefore, surgeons can perform edentulous site preparation and implant placement according to the real-time displayed relative position of patients and surgical instruments. According to a systematic review and meta-analysis, the entry, exit and angle deviations of dynamic CAIS (dCAIS) were 0.91 mm, 1.04 mm and 3.7°, respectively.[11] However, because computer screens and real surgical fields are usually separated, surgeons have to shift the view between them, which may lead to surgeons missing important cues in either the surgical field or dynamic navigation system, thereby increasing the risk of postoperative adverse effects. Moreover, frequent view shifts may interrupt the continuity of the surgery and cause surgeon fatigue, thus prolonging the surgical time and compromising the accuracy of dental implants.[12]

Augmented reality (AR) is a technology that can immerse virtual digital images in the real world through a head-mounted device (HMD) or an integral videography (IV) overlay device.[13,14] With the help of AR technology, dental implant planning paths, 3D reconstructed models, computer screens and calibrated surgical instruments can be merged with the real environment.[15] Therefore, the integration of AR enables surgeons to pay attention to real-time information obtained from dynamic navigation and from actual surgical sites simultaneously, improving the continuity and flexibility of dCAIS. Pellegrino et al. and Yotpibulwong et al. applied an HMD to directly project the computer interface of a dynamic navigation system in a real environment around the patient.[16,17] Ochandiano et al. developed a smartphone-based AR navigation system that displays bone structures and planned dental implants.[18] Ma et al. and Jiang et al. used an IV overlay device to superimpose the inferior alveolar nerve and planned dental implant paths in mandible phantoms.[14,19] Lin et al. combined a surgical template and AR to guide osteotomy with a virtual auxiliary line and drill stop.[20] The core concept is to overlay a virtual presurgical plan over the actual surgical site and enable real-time guidance, with or without integrating auxiliary guiding information such as a drill direction line, indication crosshairs, an alarm system based on color change, and real-time lateral and angle deviations between the handpiece and planned paths.[12,13,19–21] Liu et al. reported a mixed reality (MR)-based navigation method in dental implant surgery.[12] However, the core technology in the study can still be ascribed to non-in situ AR according to previous reviews.[22,23] The accuracy of AR-based navigation in dental implant surgery has been verified, with global entry, exit and angle deviations of 0.89 mm, 1.47 mm and 3.96°, respectively.[9] The comparison accuracy of AR-based dynamic navigation, static guide and free-hand was conducted by Kivovics et al., and AR-based dynamic navigation yielded a comparable accuracy with static guides.[13] However, to the best of our knowledge, few studies have focused on comparing the accuracy between AR-based dynamic navigation and dynamic navigation systems.

The aim of the *in vitro* study was to compare the accuracy of dental implant placement using AR-based dynamic navigation and conventional dynamic navigation systems. The null hypothesis was that there is no significant difference with regard to the accuracy of dental implant placement using the two navigation systems.

Materials and methods

Study design

This *in vitro study* was approved by the ethics committee (SH9H-2023-T82-1). The sample size was calculated based on two previous studies using G*power 3.1 software, where α was 0.05 and the power was set at 95%.[13,24] The minimal sample size was 28 dental implants in each group. Four types of jaws were chosen: edentulous maxilla, edentulous mandible, partially edentulous maxilla and partially edentulous mandible. To mimic real clinical conditions, the phantoms were reconstructed and printed from cone-beam computed tomography (CBCT) images of real patients. For each type, eight patients were included. Patients who required mass guided bone regeneration (GBR) surgery or zygomatic implant surgery were excluded. Each collected CBCT was used to generate two identical phantoms, and the phantoms were allocated to the AR-based dynamic navigation group (ARDN) and conventional dynamic navigation group (DN).

Phantom preparation and planning

The phantoms were reconstructed and manufactured by stereolithography using Somos® EvoLVe 128 resin (Covestro AG, Leverkusen, Germany). To ensure registration accuracy, eight mini-screws (φ1.7 mm × 10 mm) (Jianwei, Shenzhen, China) were inserted into both partially edentulous and edentulous phantoms as fiducial markers according to a previous study.[25,26] For 3D dental implant planning, a preoperative CBCT scan (Planmeca Oy, Helsinki, Finland) for each phantom was taken with the following parameters: 96 kV; 7.1 mA; voxel size of 0.4 mm. Dental implants were planned in an in-house Dental-Helper software (Shanghai, China) according to the residual alveolar bone.[7] For the edentulous maxilla, implants were planned at the incisor, canine, first premolar and first molar on both sides, while in the edentulous mandible, six dental implants were assigned at the lateral incisor, second premolar and first molar on the left and right sides. For phantoms with insufficient residual alveolar volume in the posterior region, two axial implants were planned at the lateral incisor combined with two tilted implants at the premolar region on both sides. Dental implants were placed in edentulous sites in partially edentulous jaws. To simulate normal mouth opening, the phantoms were then mounted on a platform that was fixed on a table by a bench vice (Fig. 1a and b).

AR-based dynamic navigation protocol

A reference frame with three reflective spheres was fixed on the residual alveolar bone. The CBCT scans and corresponding surgical plans were imported into MR-SNS software (Shanghai, China), and the reconstructed virtual phantom and planning paths were imported into HoloLens 2 (Microsoft Corp., Redmond, WA, USA). The infrared camera was set properly to track the phantom, handpiece and HoloLens 2 (Microsoft Corp.) simultaneously. The registration of the phantom and calibration of the drill were performed according to a previous study.[7] The registration of HoloLens 2 (Microsoft Corp.) was conducted using a registration cube that loads 4 reflective spheres.[27] The surgeon should wear HoloLens 2 and hold the registration cube to match four vertices of the cube to the corresponding vertices of the virtual cube displayed in HoloLens 2 (Fig. 2). To reduce random error and improve registration accuracy, four groups of vertices in four different positions, a total of 16 vertices, were used for registration. Then, the virtual phantom and planning paths were superimposed on the real phantom. Due to the simultaneous localization and mapping (SLAM) technology integrated into HoloLens 2 (Microsoft Corp.), the virtual phantom and planning paths can remain in place when the head of the surgeon moves or turns.[28] Therefore, surgeons can check the accuracy of superimposition from multiple perspectives. The virtual phantom was used to check the accuracy of superimposition; if satisfactory, the surgeon could conceal the virtual phantom by touching the "Model" button in the air, and the planning paths were then left. Then, the surgeon conducted the osteotomy procedure by adjusting the position between the drill and virtual dental implant path (Fig. 1d). The sequencing drilling procedure was adopted according to the manufacturer's protocols, and a dental implant (φ4.1 mm × 10 mm) (Institut Straumann AG, Basel, Switzerland) was finally placed under the guidance of an AR-based navigation system.

Dynamic navigation protocol

After CBCT data and planning paths were imported into BeiDou-SNS software (Shanghai, China), registration and drill calibration were conducted. Then, implant bed preparation and implant placement were performed under the guidance of the dynamic navigation system (Fig. 1c). To reduce participant bias, all phantom experiments were performed by one surgeon (B.T) who is familiar with dCAIS and has placed hundreds of dental implants in phantoms under guidance of the dynamic navigation system.[7]

Accuracy evaluation

Postoperative CBCT (Planmeca Oy) was performed with the same parameters as the preoperative CBCT. The pre- and postoperative CBCT images and corresponding planning were imported into Brainlab CMF 3.0.6 (BrainLAB AG, Munich, Germany) software. After image fusion, the global coronal, global apical and angular deviations were calculated by obtaining the coordinates at the center of the coronal and apical planes (Fig. 3). All deviations were measured and calculated by an investigator (Y.S) who was blinded to the group assignment of the phantoms.

Statistical analysis

Statistical analysis was performed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). The normal distribution of data was evaluated by the Shapiro–Wilk test. Descriptive statistical parameters, including the mean, standard deviation, 25th-75th percentile, and minimum–maximum value, were reported. A linear mixed model with a

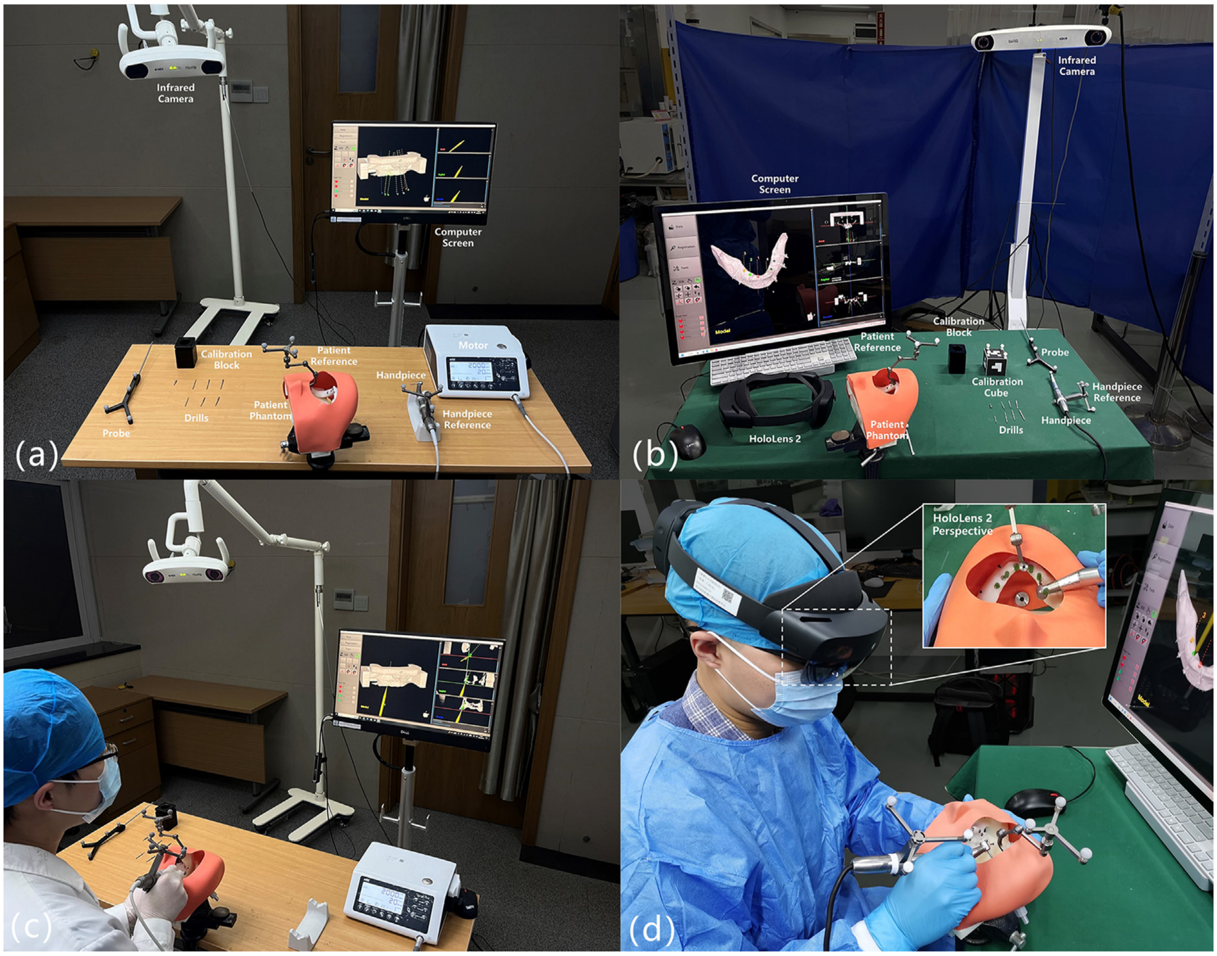

Figure 1 Overview of the hardware components and experimental setup. (a) and (c) The dynamic navigation system group. (b) and (d) The AR-based dynamic navigation system group.

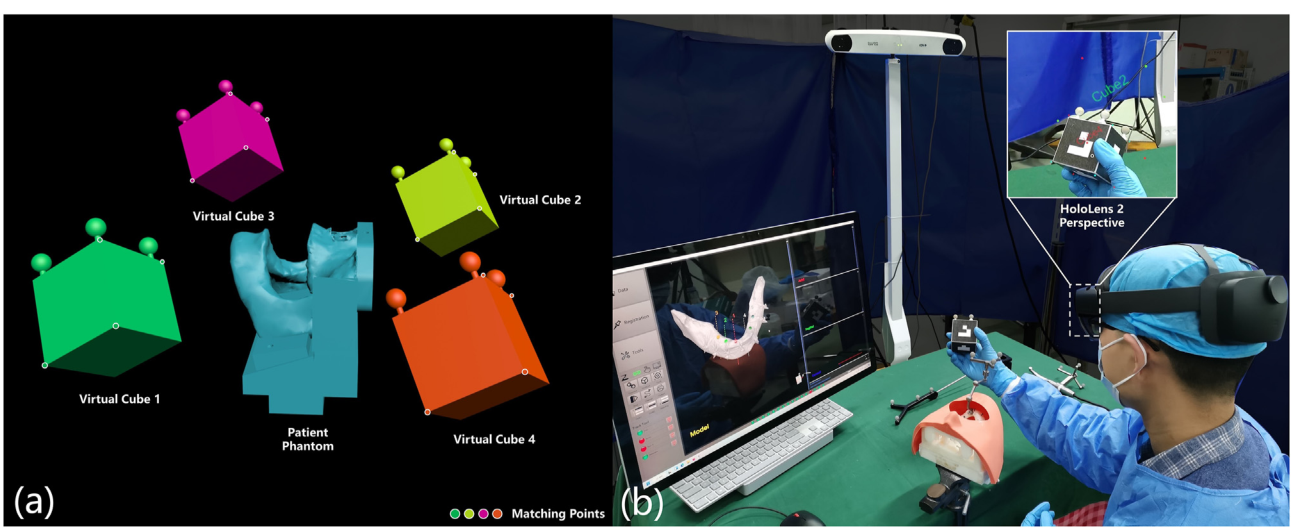

Figure 2 The registration procedure of HoloLens 2. (a) The diagram of registration. (b) Overview and HoloLens 2 perspective of the registration procedure.

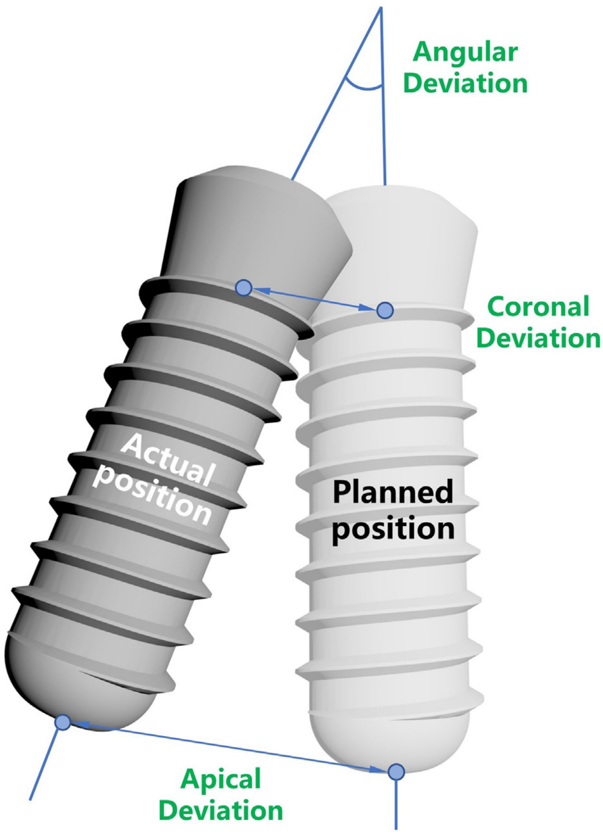

Figure 3 Illustration of deviations between planned and actual implants.

Table 1 Surgical sites for dental implant placement.

Partially edentulous				Edentulous			
Site	Number	Site	Number	Site	Number	Site	Number
11	2	32	1	11	2	32	8
12	2	34	1	12	6	34	8
14	2	35	2	13	2	36	7
15	2	36	1	14	8	42	8
16	3	37	4	16	3	44	8
17	1	42	1	21	2	46	7
21	2	44	1	22	6		
22	2	45	1	23	2		
24	1	46	2	24	8		
25	1	47	1	26	3		

random intercept was used to evaluate the comparative accuracy of the ARDN and DN groups and to analyze potential influencing factors, including tooth position and phantom type (edentulous and partially edentulous). $P<.05$ was considered to indicate a significant difference.

Results

Sixty-four phantoms were used for dental implant placement, and a total of 242 dental implants were placed. The surgical sites of the dental implants are shown in Table 1. The global coronal, global apical and angular deviations with regard to groups, phantom type and jaws are summarized in Table 2 and Table 3. The three deviations of the ARDN group were 1.31 $\pm$ 0.67 mm, 1.36 $\pm$ 0.67 mm and 3.72 $\pm$ 2.13°, respectively, while those of the DN group were 1.18 $\pm$ 0.59 mm, 1.39 $\pm$ 0.55 mm and 3.1 $\pm$ 1.56°, respectively. Due to the lack of independence of implants, a linear mixed model was applied where the group, phantom type (edentulous and partially edentulous) and tooth position (the universal teeth numbering system was adopted here) were treated as fixed effects, and the intercept was set as the random effect. Because the original deviations were not normally distributed, square root normal transformation was used. The covariance structure was chosen as the unstructured structure (UN). There was no significant difference regarding the global coronal and apical deviations ($P = 0.16$ and 0.6, respectively), while a significant difference was found in angular deviation ($P = 0.02$) (Fig. 4). The phantom type and tooth position had no significant effect on the global coronal deviation ($P = 0.25$ and 0.61, respectively), global apical deviation ($P = 0.37$ and 0.06, respectively) and angular deviation ($P = 0.81$ and 0.54, respectively).

Discussion

The present study demonstrated that AR-based dynamic navigation yields a comparable accuracy to the conventional dynamic navigation system regarding coronal and apical deviations, but a significantly higher angular deviation was detected in the AR-based dynamic navigation group.

In the present study, an AR-based dynamic navigation system was developed and achieved high accuracy with global coronal, apical and angular deviations of 1.31 $\pm$ 0.67 mm, 1.36 $\pm$ 0.67 mm and 3.72 $\pm$ 2.13°, respectively, which were similar to previous studies.[9,13,19]

Table 2 Deviations of dental implants in ARDN (AR-based dynamic navigation) and DN (Dynamic navigation) groups.

	Group	Mean ($\pm$SD)	Median	P_{25}–P_{75}	Min-Max	*P* value
Global coronal deviation (mm)	ARDN	1.31 $\pm$ 0.67	1.23	0.84–1.68	0.2–4.17	0.16
	DN	1.18 $\pm$ 0.59	1.2	0.68–1.6	0.14–2.86	
Global apical deviation (mm)	ARDN	1.36 $\pm$ 0.67	1.23	0.86–1.76	0.12–4.11	0.6
	DN	1.39 $\pm$ 0.55	1.43	1.1–1.76	0.28–2.91	
Angular deviation (∘)	ARDN	3.72 $\pm$ 2.13	3.53	2.44–4.36	0.37–12.79	0.02*
	DN	3.1 $\pm$ 1.56	2.99	1.92–4.07	0.52–7.9	

*$P < 0.05$; SD, standard deviation; P^{25}, lower quartile; P_{75}, upper quartile; Min, minimum value; Max, Maximum value.

Table 3 Deviations regarding the maxilla and mandible of the ARDN (AR-based dynamic navigation) and DN (Dynamic navigation) groups.

		ARDN group			DN group		
		Global coronal deviation (mm)	Global apical deviation (mm)	Angular deviation (°)	Global coronal deviation (mm)	Global apical deviation (mm)	Angular deviation (°)
Edentulous	Maxilla	1.25 ± 0.56	1.23 ± 0.6	3.98 ± 1.94	1.29 ± 0.65	1.49 ± 0.61	3 ± 1.38
	Mandible	1.43 ± 0.72	1.52 ± 0.74	3.26 ± 1.61	1.15 ± 0.6	1.32 ± 0.49	3.16 ± 1.66
Partially edentulous	Maxilla	1.2 ± 0.73	1.3 ± 0.59	4.41 ± 3.46	1.05 ± 0.47	1.38 ± 0.55	3.11 ± 1.92
	Mandible	1.25 ± 0.7	1.29 ± 0.69	3.6 ± 1.88	1.09 ± 0.55	1.35 ± 0.59	3.21 ± 1.36

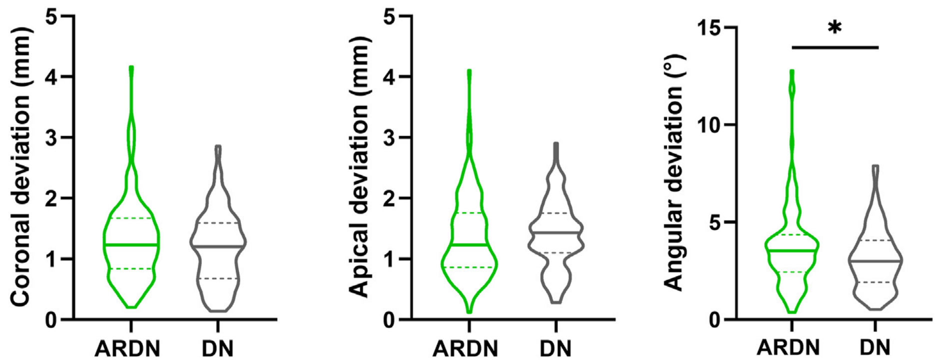

Figure 4 Comparison of the deviations between ARDN (AR-based dynamic navigation) and DN (Dynamic navigation) groups.

For the comparison of AR-based and conventional dynamic navigation methods, AR-based navigation had a smaller lateral deviation at coronal, depth and angle deviations but a higher global coronal deviation compared with dynamic navigation.[9] However, there are only two studies included in this systematic review, and the referred dynamic navigation modalities are not the same as normal dynamic navigation, which provides axial, sagittal and coronal perspectives. The guidance of the drill to the target was realized by matching two crosshairs in one study,[21] and the other used a monitor to display the 3D relationship between the drill and path instead of offering coronal, sagittal and axial interfaces.[19] Therefore, to the best of our knowledge, the current study is the first to compare AR-based dynamic navigation and dynamic navigation approaches. A significant difference was found with regard to angular deviation of dental implants placed by the ARDN and DN groups. The potential explanations were as follows. First, surgeons have to shift perspectives to review and confirm the angle between the drill and planned path because the 3D relationship between the drills and virtual implants is not easy to observe from one perspective, and the angular deviation is hard to detect without axial observation, especially in the maxilla. The maximum angular deviation (12.79°) was found at the right first molar in the maxilla. However, a dynamic navigation system can provide three separated interfaces, which enables surgeons to visualize three directions at the same time. This result is consistent with a previous study showing that the angular deviation of the AR-based dynamic CAIS was slightly higher than that of static CAIS.[13] In addition, the virtual implants, which are the same size as real objects, are projected onto phantoms. Therefore, small deviations may not be found by surgeons in time. However, dynamic navigation systems can enlarge virtual implants and drills on computer screens, so any deviations can be detected easily. To further improve its accuracy with regards to the angle, a combination of static guide and AR-based dynamic navigation approach could be a choice, where the angular deviation in the mandible phantom was 2.7 ± 1.55° and that was 3.33 ± 1.42° in the maxilla.[20] Moreover, a display of navigation system screens or real-time deviations in the perspective of HoloLens 2 may be another choice.[12,16,17]

The limitation of the present study is that no auxiliary information for guidance was added to the AR system, so the surgeon had to perceive deviations based on the surgical and manipulation experience. Moreover, the result should be restricted to the modality of the AR-based navigation used in the current study. The comparative accuracy of other AR modalities should be further investigated. The time and investment needed for setup and training may slow its speed in clinical application. Then, the bulky headset may evoke a feeling of refusal, especially for surgeons who have an illness of the cervical spine. An adjustable AR headset is a potential solution. Finally, the results of the current *in vitro* study with a small sample size should be carefully extended to a real clinical environment, and its feasibility, accuracy and reliability must be further evaluated in clinical studies.

In summary, this *in vitro* study demonstrated that the AR-based dynamic navigation approach had a comparable accuracy to the conventional dynamic navigation system in global coronal and apical deviation but had a higher angular deviation. This AR-based navigation system provides in situ AR navigation and facilitates precise and convenient dental implant navigation surgery. However, the angle of implant site preparation and implant placement should be reconfirmed when the AR-based dynamic navigation system is implemented in dental implant surgery.

Declaration of competing interest

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

Acknowledgments

This work was supported by the grants/awards of Clinical Research Plan of SHDC (SHDC2020CR3049B), Medical Engineering Cross Research Fund of "Jiao Tong University Star" Program of Shanghai Jiao Tong University (YG2021QN72), CAMS Innovation Fund for Medical Sciences (CIFMS) (2019-I2M-5-037), Research Discipline fund from Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine (KQYJXK2020); Huangpu District Industrial Support Fund (XK2020014).

References

1. Kaewsiri D, Panmekiate S, Subbalekha K, Mattheos N, Pimkhaokham A. The accuracy of static vs. dynamic computer-assisted implant surgery in single tooth space: a randomized controlled trial. *Clin Oral Implants Res* 2019;30:505–14.
2. D'Haese J, Ackhurst J, Wismeijer D, De Bruyn H, Tahmaseb A. Current state of the art of computer-guided implant surgery. *Periodontol* 2000 2017;73:121–33.
3. Smitkarn P, Subbalekha K, Mattheos N, Pimkhaokham A. The accuracy of single-tooth implants placed using fully digital-guided surgery and freehand implant surgery. *J Clin Periodontol* 2019;46:949–57.
4. Van Assche N, Vercruyssen M, Coucke W, Teughels W, Jacobs R, Quirynen M. Accuracy of computer-aided implant placement. *Clin Oral Implants Res* 2012;23:112–23.
5. Pimkhaokham A, Jiaranuchart S, Kaboosaya B, Arunjaroensuk S, Subbalekha K, Mattheos N. Can computer-assisted implant surgery improve clinical outcomes and reduce the frequency and intensity of complications in implant dentistry? a critical review. *Periodontol* 2022;90:197–223.
6. Siqueira R, Chen Z, Galli M, Saleh I, Wang HL, Chan HL. Does a fully digital workflow improve the accuracy of computer-assisted implant surgery in partially edentulous patients? a systematic review of clinical trials. *Clin Implant Dent Relat Res* 2020;22:660–71.
7. Tao B, Feng Y, Fan X, et al. Accuracy of dental implant surgery using dynamic navigation and robotic systems: an in vitro study. *J Dent* 2022;123:104170.
8. Chackartchi T, Romanos GE, Parkanyi L, Schwarz F, Sculean A. Reducing errors in guided implant surgery to optimize treatment outcomes. *Periodontol* 2022;88:64–72.
9. Mai HN, Dam VV, Lee DH. Accuracy of augmented reality-assisted navigation in dental implant surgery: systematic review and meta-analysis. *J Med Internet Res* 2023;25:e42040.
10. Wei SM, Zhu Y, Wei JX, Zhang CN, Shi JY, Lai HC. Accuracy of dynamic navigation in implant surgery: a systematic review and meta-analysis. *Clin Oral Implants Res* 2021;32:383–93.
11. Schnutenhaus S, Edelmann C, Knipper A, Luthardt RG. Accuracy of dynamic computer-assisted implant placement: a systematic review and meta-analysis of clinical and in vitro studies. *J Clin Med* 2021;10:704.
12. Liu L, Wang X, Guan M, et al. A mixed reality-based navigation method for dental implant navigation method: a pilot study. *Comput Biol Med* 2023;154:106568.
13. Kivovics M, Takács A, Pénzes D, Németh O, Mijiritsky E. Accuracy of dental implant placement using augmented reality-based navigation, static computer assisted implant surgery, and the free-hand method: an in vitro study. *J Dent* 2022;119:104070.
14. Ma L, Jiang W, Zhang B, et al. Augmented reality surgical navigation with accurate CBCT-patient registration for dental implant placement. *Med Biol Eng Comput* 2019;57:47–57.
15. Gsaxner C, Li J, Pepe A, et al. The HoloLens in medicine: a systematic review and taxonomy. *Med Image Anal* 2023;85:102757.
16. Pellegrino G, Mangano C, Mangano R, Ferri A, Taraschi V, Marchetti C. Augmented reality for dental implantology: a pilot clinical report of two cases. *BMC Oral Health* 2019;19:158.
17. Yotpibulwong T, Arunjaroensuk S, Pimkhaokham A. Application of augmented reality with navigation system and laboratory guide affected on the deviation of dental implant-a pilot clinical study. *RSU Int Res Conf* 2022:193–201.
18. Ochandiano S, García-Mato D, Gonzalez-Alvarez A, et al. Computer-assisted dental implant placement following free flap reconstruction: virtual planning, CAD/CAM templates, dynamic navigation and augmented reality. *Front Oncol* 2021;11:754943.
19. Jiang W, Ma L, Zhang B, et al. Evaluation of the 3D augmented reality-guided intraoperative positioning of dental implants in edentulous mandibular models. *Int J Oral Maxillofac Implants* 2018;33:1219–28.
20. Lin YK, Yau HT, Wang IC, Zheng C, Chung KH. A novel dental implant guided surgery based on integration of surgical template and augmented reality. *Clin Implant Dent Relat Res* 2015;17:543–53.
21. Vigh B, Müller S, Ristow O, et al. The use of a head-mounted display in oral implantology: a feasibility study. *Int J Comput Assist Radiol Surg* 2014;9:71–8.
22. Ma L, Huang T, Wang J, Liao H. Visualization, registration and tracking techniques for augmented reality guided surgery: a review. *Phys Med Biol* 2022;68.
23. Lungu AJ, Swinkels W, Claesen L, Tu P, Egger J, Chen X. A review on the applications of virtual reality, augmented reality and mixed reality in surgical simulation: an extension to different kinds of surgery. *Expet Rev Med Dev* 2021;18:47–62.
24. Fernández-Gil Á, Gil HS, Velasco MG, Moreno Vázquez JC. An in vitro model to evaluate the accuracy of guided implant placement based on the surgeon's experience. *Int J Oral Maxillofac Implants* 2017;32:151–4.
25. Pei X, Liu X, Iao S, Ma F, Li H, Sun F. Accuracy of 3 calibration methods of computer-assisted dynamic navigation for implant placement: an in vitro study. *J Prosthet Dent* 2022. S0022-3913(22)189-5.
26. Tao B, Feng Y, Fan X, et al. The accuracy of a novel image-guided hybrid robotic system for dental implant placement: an in vitro study. *Int J Med Robot* 2023;19:e2452.
27. Tu P, Qin C, Guo Y, et al. Ultrasound image guided and mixed reality-based surgical system with real-time soft tissue deformation computing for robotic cervical pedicle screw placement. *IEEE Trans Biomed Eng* 2022;69:2593–603.
28. Tu P, Gao Y, Lungu AJ, Li D, Wang H, Chen X. Augmented reality based navigation for distal interlocking of intramedullary nails utilizing Microsoft HoloLens 2. *Comput Biol Med* 2021;133:104402.