THE JOURNAL OF PROSTHETIC DENTISTRY

CLINICAL RESEARCH

Accuracy and safety of implant placement with a novel semi-autonomous robotic-assisted surgical system: A translational research study

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ABSTRACT

Statement of problem. Translational studies evaluating the feasibility, accuracy, and safety of semi-autonomous implant robots, from model test to animal experiment and clinical trial, are currently lacking.

Purpose. The purpose of this study was to evaluate the accuracy and safety of a novel semi-autonomous robotic-assisted surgical system (sa-RASS) in implant placement.

Material and methods. A translational study was conducted to assess the application of the sa-RASS in a model test, an animal experiment, and a clinical controlled trial. The study included 45 resin models in the model test, 7 male beagle dogs in the animal experiment, and 60 participants who were recruited and randomly assigned to a freehand or a sa-RASS group in the clinical trial. The accuracy, surgical morbidity, complications, operator ratings of instrument safety, and satisfaction were recorded. Cone beam computed tomography data were used to evaluate deviations between planned and placed implants. The data on deviations were analyzed using the Mann-Whitney U test. A linear regression model was established to analyze the variations in the deviations (α=.05).

Results. The mean ±standard deviation of the platform, apex, and angulation deviations were 0.98 ±0.53 mm, 1.10 ±0.52 mm, and 1.45 ±0.60 degrees in the model test and 0.58 ±0.19, 0.59 ±0.22 mm, and 1.88 ±0.71 degrees in the animal experiment. In the clinical controlled study, the platform, apex, and angular deviations of the sa-RASS group and freehand group were 0.93 ±0.50 mm versus 1.45 ±0.86 mm (P<.01), 1.07 ±0.63 mm versus 2.05 ±1.16 mm (P<.001), and 3.10 ±1.68 degrees versus 7.94 ±3.55 degrees (P<.001). No complications, such as early implant failure, intraoperative hemorrhage, injuries to adjacent structures, or implant displacement beyond the apical anatomic limit, were observed in the sa-RASS group. The results of the linear regression model showed that age, sex, bone density, implant position, implant diameter, and length did not significantly influence the accuracy of implantation at the apex or the angulation (P>.05).

Conclusions. The sa-RASS was found to be more accurate than freehand placement, with high operational safety and low surgical morbidity. (J Prosthet Dent 2025;133:1304-1314)

Robotic surgery is a reality in implant dentistry.[1–7] It can be traced back to the first study on robotic-assisted implant placement in 2002[5] and the Federal Drug Administration (FDA) approval of the first robotic dental surgical system (Yomi; Neocis Inc) in 2017.[6] Zhao et al[7] successfully developed an autonomous implant robot

Supported by the Zhejiang Provincial Medical and Health Science and Technology Program Grant (WKJ-ZJ-2328, 2023KY035) and by the Zhejiang Traditional Chinese Medicine Administration Program Grant (2023ZL242), PR China.
Y.F., W.L.H., and D.Y.D. participated in the research of the robot to provide technical support. This study did not receive any financial support from any company. No company intervened in the process of the model experiment and the clinical trial. The other authors report no conflict of interest related to this study.
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Clinical Implications

This study provided data support for promoting the development of the sa-RASS technology and the standardization of semi-autonomous robot implantation schemes.

system in 2017, and, over the past 2 years, there has been a notable surge in the research on robotic technology tailored for implantation procedures.[8–12] Robotic-assisted surgical systems use advanced sensor technology and intelligent control algorithms to sense information about the patient's oral anatomy in real time. They also provide the surgeon with accurate operation paths and angles, as well as positional guidance through the navigation function.[9,10,12] By using the system, surgeons may obtain an accurate implant position and reduce accuracy errors and risks during surgery.[13]

According to the level of autonomy of the robot, the implant robot has been classified into autonomous, semi-autonomous, and passive types.[14,15] Recent research has revealed promising progress in the accuracy of autonomous implant robots, marking encouraging advancements in this field.[8,16–19] In a model experiment, Chen et al[16] compared the accuracy of implant placement using a dynamic navigation and an autonomous robotic system (Remebot; Beijing Baihui Weikang Technology Co). They reported that the mean deviations of the autonomous robot were 0.86 ±0.36 mm at the platform, 0.77 ±0.34 mm at the apex, and 1.94 ±0.66 degrees for angulation, values that are more accurate than the navigation.[16] Additionally, Tao et al[9] reported on a semi-autonomous robotic system under development and illustrated the similar deviations (0.83 ±0.55 mm at the platform, 0.91 ±0.56 mm at the apex, and 1 ±0.48 degrees for angulation) in a model test. The mean deviations of these studies were more accurate than those of earlier studies (1.42 ±0.70 mm).[5,8] However, clinical studies are still in the early stages and have mostly focused on autonomous robots, with limited research on semi-autonomous robots.[16,18–22] In addition, clinical studies of semi-autonomous robots have only been reported in case series and a few retrospective cohort studies.[13,22–24] Most of the retrospective studies included both single missing tooth implant placement and edentulous implantation in the same study, which may have skewed the data.[22–24] Moreover, making direct comparisons of semi-autonomous robotic research is not feasible because of variations in experimental models and clinical trials, as well as differences between different semi-autonomous robotic systems.[9,23,24] Comprehensive studies that maintained the same operator, same robotic system, and same software program design throughout the entirety of the research process, from model test to clinical trial, are sparse.[24]

Therefore, this translational study aimed to test the research hypotheses that a novel semi-autonomous robotic-assisted surgical system (sa-RASS) would demonstrate operational feasibility, safety, and high accuracy in implant placement during a model test, an animal experiment, and a clinical trial and would achieve greater accuracy compared with freehand.

MATERIAL AND METHODS

This study was carried out according to the principles of the Helsinki Declaration, revised in 2008. It consisted of a model test, an animal experiment, and a clinical randomized controlled trial of a novel semi-autonomous robot for dental implant treatments.

The sa-RASS is a haptic and machine-vision-controlled surgical system that consists of 5 main components: a robot arm with an end effector, binocular camera, industrial control computer, integrating platform, and position marker (Fig. 1). The sa-RASS is a semi-autonomous collaborative robot that encompasses both autonomous and passively triggered actions. The autonomous actions include positioning the robotic arm and handpiece, positioning and maintaining the drilling direction, and tracking the patient's motion. Within a certain range of the implantation site (<10 mm), the autonomous process will be triggered. The act of drilling is a passively initiated procedure that requires the surgeon to hold the button on the handpiece to initiate the drilling process. During the drilling procedure, the robotic system automatically provides angular and position control, enabling the surgeon to move the drill forward or backward. Once the drill reaches the intended depth, the robotic system halts the handpiece to prevent any additional drilling (Fig. 2). Meanwhile, the surgeon can also monitor feedback data on the implantation process such as depth (mm), lateral distance (mm), and angular deviation on the screen.

In the model test, a radiopaque resin dentition model with a space of 7 missing teeth (Implant practice model; Star Medical Equipment Co) was used to assess the feasibility and in vitro accuracy of the sa-RASS (Fig. 3). In the first stage of development, the radiopaque resin models were fixed to a table to verify the feasibility of the sa-RASS (Stage 1) and preliminarily verify the accuracy of the sa-RASS for in vitro implant placement. In the second stage, the ability to track the patient's head movements was added, and the models were placed in a virtual head model rather than rigidly attached to a table.

In the animal experiment, 7 male beagle dogs, each weighing between 13 and 15 kg and with an average age

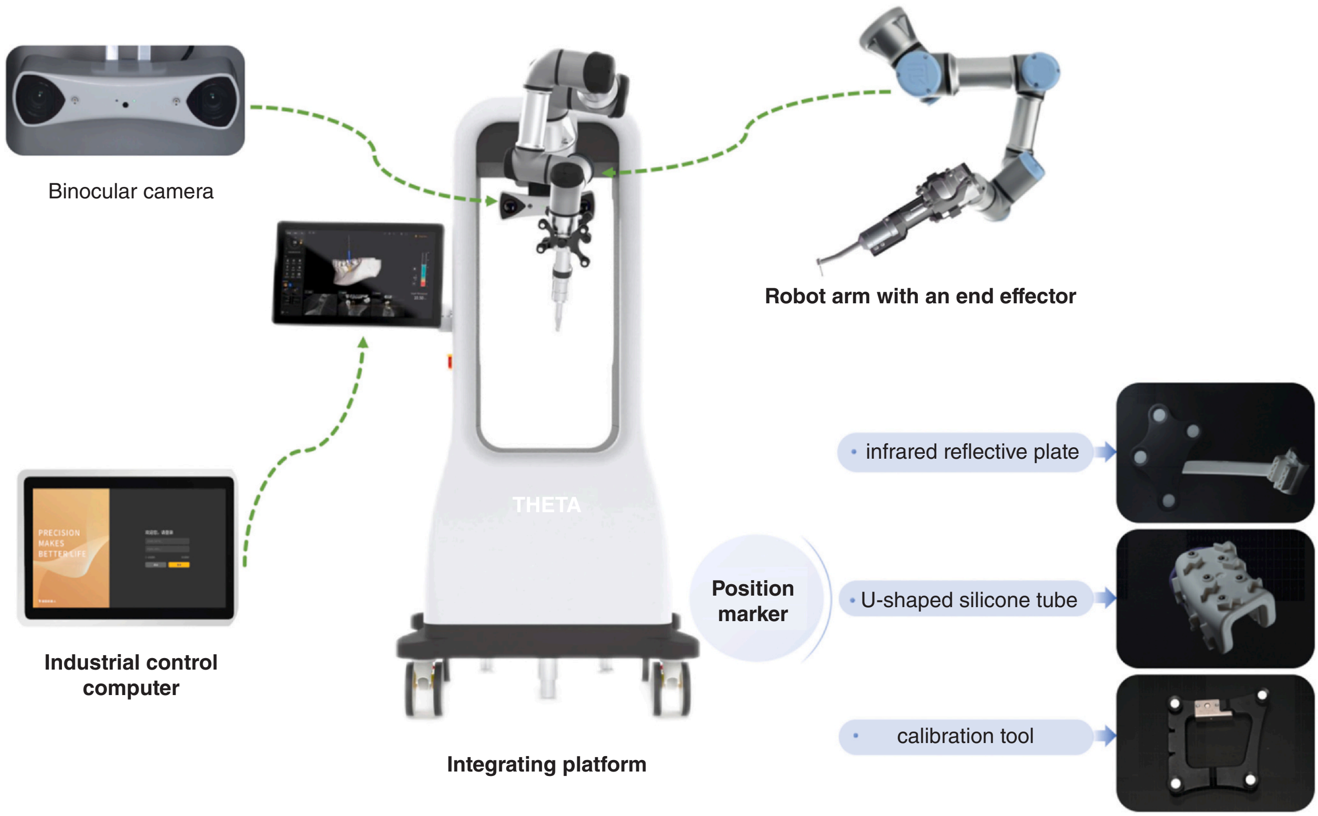

Figure 1. Architecture of sa-RASS. sa-RASS, semi-autonomous robotic-assisted surgical system.

of 2 years, were used. These dogs were accommodated at the laboratory animal research center of Zhejiang Chinese Medicine University in Hangzhou, China. All procedures were approved (Approval No. 12759) and conducted in accordance with the guidelines for institutional Animal Care and Use of Laboratory Animals. All surgical procedures were performed under general anesthesia with inhaled isoflurane. The dogs were fixed on the operating table in lateral recumbent position. After intraoral and extraoral disinfection, the maxillary incisor and maxillary first molar were extracted under local anesthesia. After 4 weeks of healing, an incision was made through the mucosa to the crest of the alveolar ridge. Then, the surgeon (Y.F.) made an osteotomy and placed an implant (Straumann TL; Institute Straumann AG) using the sa-RASS as described previously (Fig. 4A-C). Appropriate therapy was administered if the behavior of the dogs indicated any adverse reactions or pain after the surgery.

The clinical study was designed as a pilot single-blind, randomized controlled trial (RCT) to evaluate the in vivo accuracy of freehand and sa-RASS in implant placement. Written informed consent was obtained from all participants according to the guidelines of the ethics committee of Zhejiang Provincial People's Hospital (Approval No. 2022013). Patients who visited the department of stomatology at Zhejiang Provincial People's Hospital (Affiliated People's Hospital) for implant treatment were screened. The inclusion criteria were aged between 18 and 70 years, good oral hygiene and systemic health (ASA class I and II), presence of a single missing tooth requiring an implant-supported restoration, mouth opening of at least 35 mm, and compliance with protocols and follow-up visits pertaining to the study. The exclusion criteria were age <18 or >70 years, uncontrolled periodontitis, uncontrolled systemic disease, severe bone defect at implant location, mouth opening <35 mm, pregnancy or lactation, radiation exposure to the head and neck area, current chemotherapy, drug or alcohol abuse, and smoking >10 cigarettes per day. Patients who met the criteria were enrolled in the study and received the experimental treatments from June to October 2023. All selected patients underwent periodontal and dental examinations before surgery and received effective periodontal treatment.

The allocation of treatments for the patients followed a randomized approach using a randomization software program (Clinical Information Management Suite, version 5; CMIS-MEDTECH). The participants were divided into 2 groups, the freehand implant surgery (FHIS) group and the sa-RASS group (the surgeon performed the implant surgery in collaboration with sa-RASS) (Fig. 4D-F), using a randomized allocation

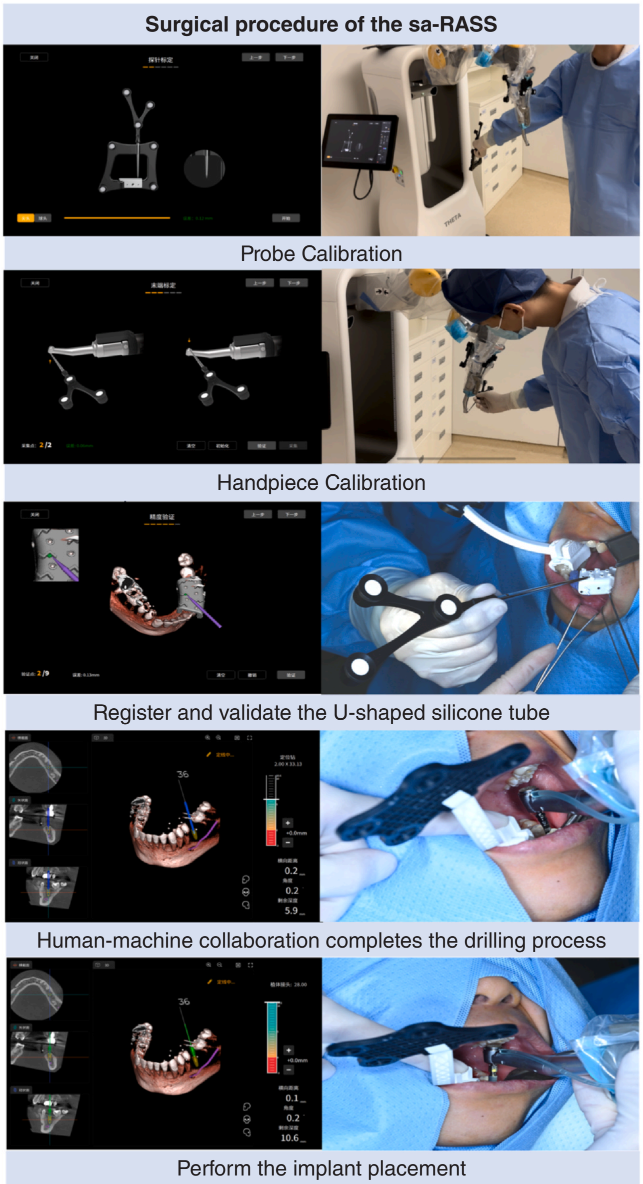

Figure 2. Workflow of sa-RASS: surgical procedure on software program (Cypress; Hangzhou Jianjia Medical Technology Co) and clinical situation. sa-RASS, semi-autonomous robotic-assisted surgical system.

system. After the allocation (Fig. 5), CBCT and intraoral scan data were imported into the robotic surgical planning software program to design the implant position for the sa-RASS group based on prosthetically driven principles.[25] Another implant planning software program (DTX Studio Implant; Nobel Biocare) was used for the freehand implant surgery group (Fig. 6).

Following intraoral and extraoral cleaning and sterilization, a surgeon (Y.F.) with experience in the sa-RASS surgery and more than 10 years of experience in freehand implantation performed the surgeries. In the sa-RASS group, the surgeon maneuvered the sa-RASS to perform the surgery as described previously. In the FHIS group, the surgeon performed the implant placement based on surgical experience to carry out the preoperative plan.

The accuracy of the implant placement, surgical morbidity, and complications were assessed as the implant dentistry core outcome set and measurement (ID-COSM).[26] Instrument evaluation was also performed as the secondary evaluation indicator, including the scores of participant satisfaction with the sa-RASS, instrument defects and safety evaluation, work stability, and the incidence of adverse events related to the sa-RASS. The postoperative pain (100-mm visual analog scale) and injuries to adjacent structures such as nerves and adjacent teeth were recorded as adverse events. Moreover, intraoperative hemorrhage, postoperative swelling, early implant loss, wound dehiscence, and infection were also recorded in the case report form.

Accuracy was evaluated using an open-source program (3D Slicer version 4.13; Harvard, https://www.slicer.org).[27] All CT scans were performed at 80 kV and 6.0 mA for 15 seconds (voxel size: 0.15 mm; grayscale:15 bits; focal spot: 0.5 mm; and field of view: 12×9 cm). The angular variations, global deviation, depth and lateral deviation at the platform and apex were calculated to describe the accuracy of the implant placement (Fig. 7). Depth deviations at the implant platform and apex were analyzed, identifying implants with an apically deeper position than planned (excessive depth deviation) for secondary analysis to assess the safety of both freehand and robot-assisted implant surgery. All measurements in the present study were performed twice by a single examiner (C.J.P.), with a 2-week interval between measurements. To assess reproducibility, an interclass correlation coefficient (ICC) analysis was conducted on the 2 sets of results.

Statistical analyses were performed with a statistical software program (IBM SPSS Statistics, v22.0; IBM Corp). The Shapiro–Wilk test was used to assess the normal distribution of the data. The mean and standard deviation (SD) were used to show the results. The groups were compared by using the Mann-Whitney U test. A linear regression model was established to analyze the variations in the deviation (α=.05).

RESULTS

A total of 45 models (10 in Stage 1 and 35 in Stage 2) and 45 implants were included in the model test. Table 1 presents the accuracy of implant placement. The Shapiro-Wilk test revealed that the data for platform deviation in Stage 2 did not follow a normal distribution. In Stage 1, the mean ±standard deviations between

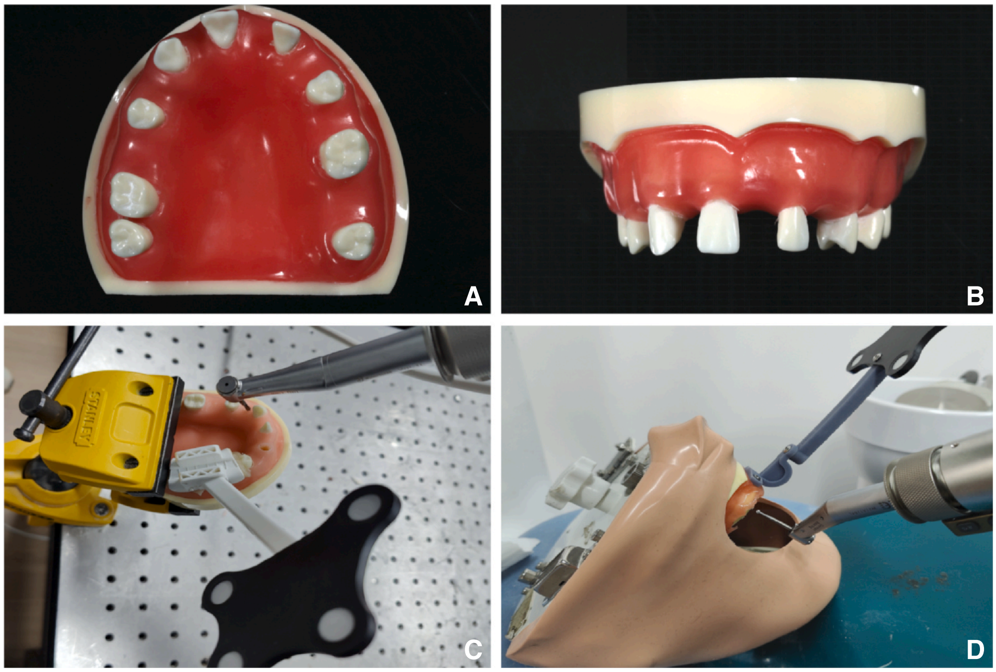

Figure 3. Model test of sa-RASS. A, Occlusion view of model. B, Frontal view of model. C, Stage one: resin arch model fixed on table rigidly for implant placement. D, Stage two: resin arch model attached to virtual head for implant placement. sa-RASS, semi-autonomous robotic-assisted surgical system.

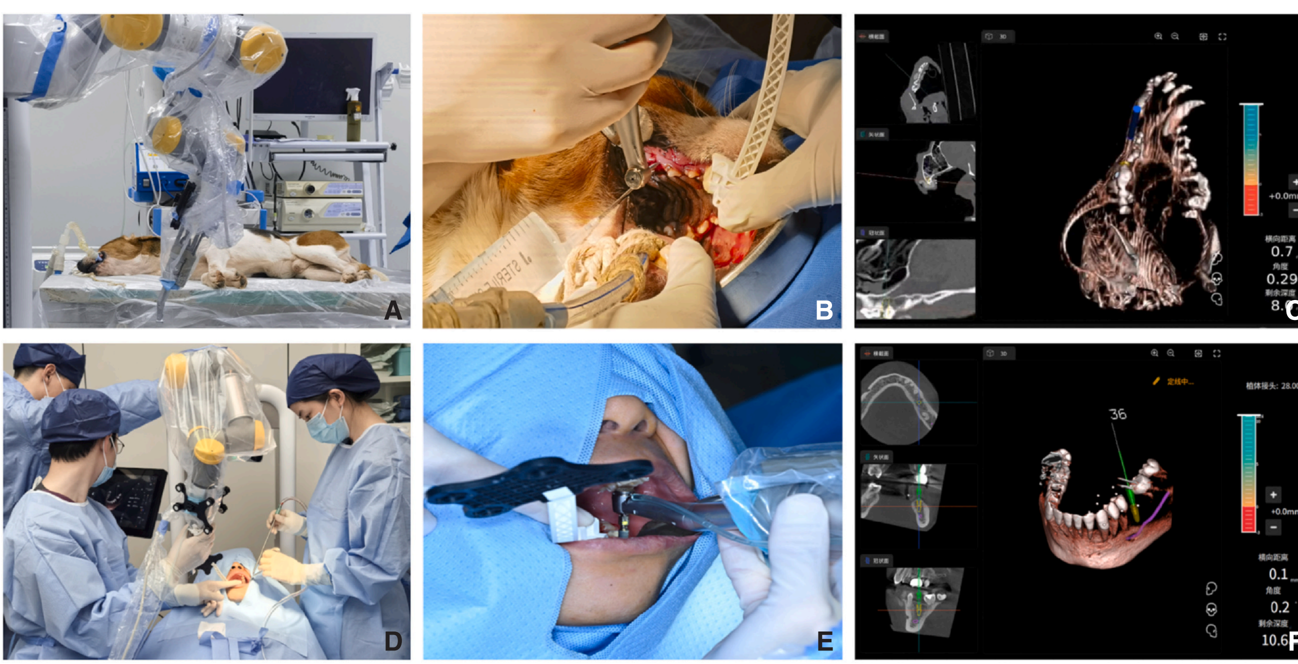

Figure 4. Animal experiment and clinical surgery of sa-RASS method. A, B, Dog under general anesthesia for implant placement using sa-RASS. C, Screen capture of implant placement procedure in dog. D, E, Process of clinical implantation with sa-RASS. F, Screen capture of implant placement procedure in jaw. sa-RASS, semi-autonomous robotic-assisted surgical system.

planned and postoperative implant positions were 1.89 ±0.50 mm at the platform, 2.05 ±0.31 mm at the apex, and 2.90 ±0.91 degrees for angulation. After integrating head movement tracking into the sa-RASS, the mean deviations for the platform, apex, and angulation were statistically significantly reduced to 0.98 ±0.53 mm, 1.10 ±0.52 mm, and 1.45 ±0.60 degrees (P<.001).

In the animal experiment, a total of 14 implants were placed. The mean ±standard deviations between planned and postoperative implant positions were 0.58 ±0.19 mm

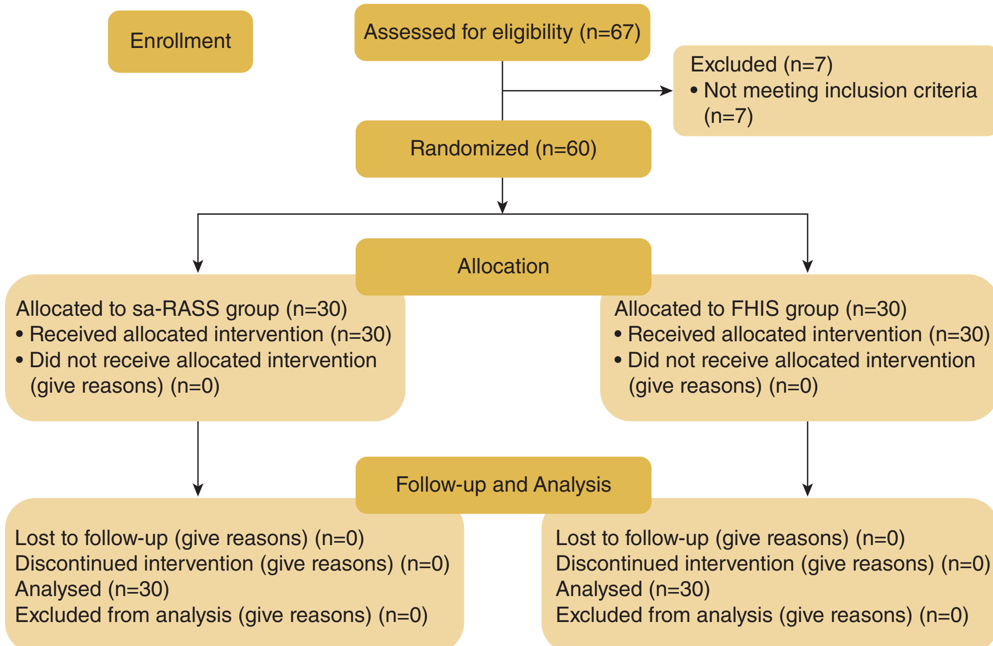

Figure 5. CONSORT diagram.

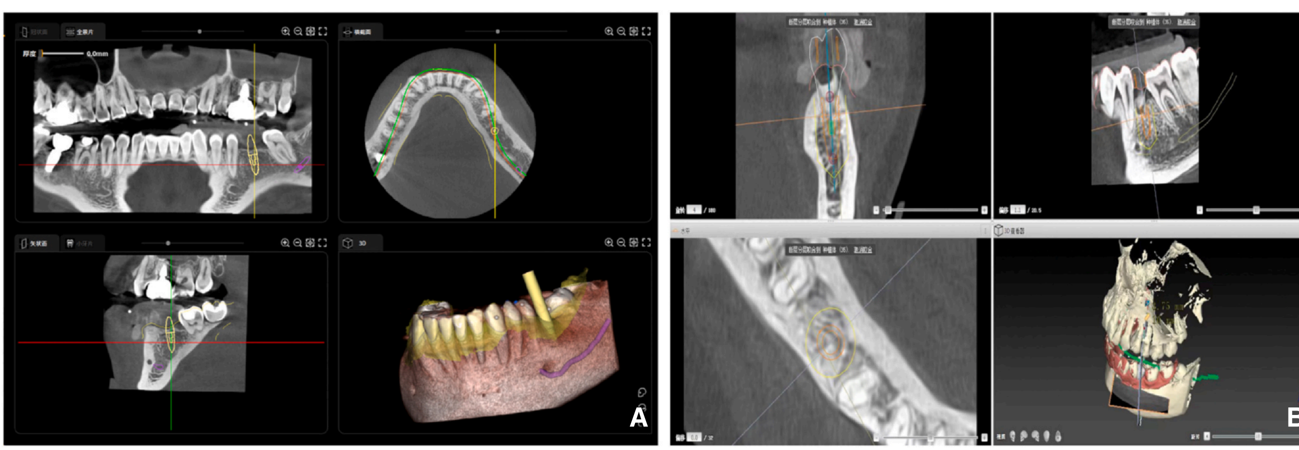

Figure 6. Schematic diagram of preoperative design scheme. A, sa-RASS group: implant position designed in software program (Cycad; Hangzhou Jianjia Medical Technology Co) of sa-RASS. B, Freehand implant surgery group: implant position designed in implant software program (DTX Studio Implant; Nobel Biocare). sa-RASS, semi-autonomous robotic-assisted surgical system.

at the platform, 0.59 ±0.22 mm at the apex, and 1.88 ±0.71 degrees for angulation (Table 2). Deviations at both the platform and apex were within 1 mm.

In the clinical research part, a total of 67 patients were screened, and 60 patients (17 men and 43 women, with a mean ±standard deviation age of 35.36 ±12.05 years) who provided informed consent and met the eligibility criteria were randomized and received the allocated treatment. The results of the deviations are presented in Table 3 and Figure 8. The ICC values were 0.920 for global platform deviation, 0.917 for global apex deviation, 0.968 for angular deviation, 0.896 for platform depth deviation, 0.761 for platform lateral deviation, 0.951 for apex depth deviation, and 0.887 for apex lateral deviation. All results exceeded 0.7, indicating high reliability.[28] The platform, apex, and angular deviations of the sa-RASS group and FHIS groups were 0.93 ±0.50 mm versus 1.45 ±0.86 mm ($P<.01$), 1.07 ±0.63 mm versus 2.05 ±1.16 mm ($P<.001$), and 3.10 ±1.68 degrees versus 7.94 ±3.55 degrees ($P<.001$). The lateral directions between the FHIS and sa-RASS groups were statistically significant ($P<.05$). However, no statistical differences were found in global depth deviation or excessively deep implantation (Table 3, Fig. 8).

The results of the linear regression model indicated statistically significant differences in apex ($P<.05$), lateral platform ($P<.01$), and angular deviations ($P<.001$) between the FHIS and sa-RASS groups (Table 4). Age influenced

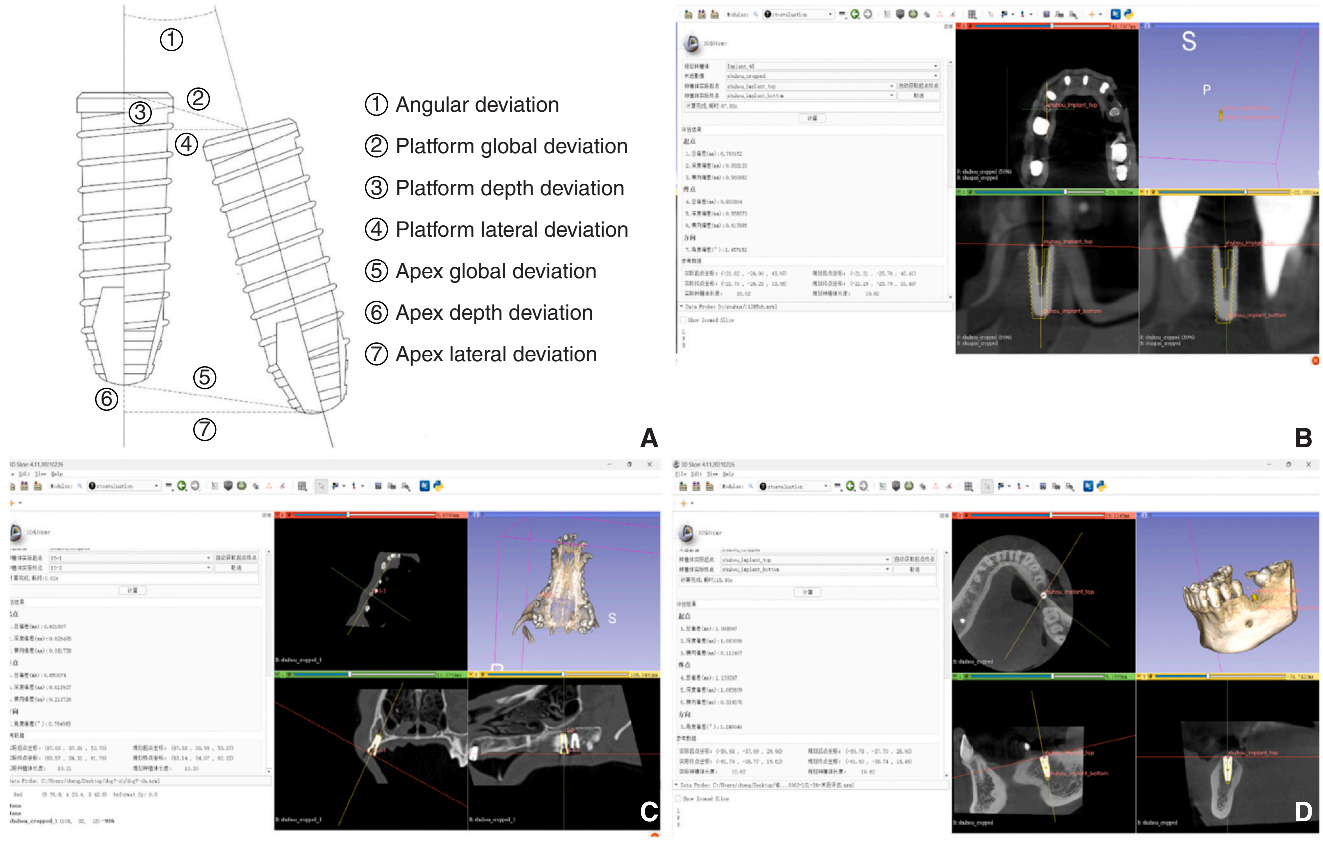

Figure 7. Measurement of implant placement accuracy. A, Illustration of deviations (platform, apex, and angulation) of implants between preoperatively planned and actual position. B-D, Fusion and calibration of planned and postoperative images of resin arch model, dog, and patient in 3D Slicer software program.

Table 1. Implant accuracy of sa-RASS in model test

Stage		Platform Deviation (mm)	Apex Deviation (mm)	Angular Deviation (Degrees)
1 (n=10)	Mean ±SD	1.89 ±0.50	2.05 ±0.31	2.90 ±0.91
	Median	1.82	2.09	2.95
	25th Percentile	1.44	1.83	1.94
	75th Percentile	2.16	2.22	3.87
2 (n=35)	Mean ±SD	0.98 ±0.53	1.10 ±0.52	1.45 ±0.60
	Median	0.92	0.98	1.44
	25th Percentile	0.63	0.79	1.08
	75th Percentile	1.23	1.37	1.88
P		<.001	<.001	<.001

sa-RASS, semi-autonomous robotic-assisted surgical system; SD, standard deviation.

Table 2. Implant accuracy of sa-RASS in animal experiment

	Platform Deviation (mm)			Apex Deviation (mm)			Angular Deviation (Degrees)
	Global	Depth	Lateral	Global	Depth	Lateral	
Mean ±SD	0.58 ±0.19	0.32 ±0.18	0.43 ±0.23	0.59 ±0.22	0.32 ±0.19	0.47 ±0.21	1.88 ±0.71
95% CI (lower bound)	0.47	0.21	0.29	0.46	0.21	0.34	1.45
95% CI (upper bound)	0.70	0.43	0.58	0.73	0.44	0.59	2.31

CI. confidence interval; sa-RASS, semi-autonomous robotic-assisted surgical system; SD, standard deviation.

the platform deviation (P<.05), particularly in the lateral direction (P<.01). Bone density affected lateral platform deviation (P<.05) and apex depth deviation (P<.05). In addition, the age, sex, bone density, implant position (maxillary or mandible), implant diameter, and length did not significantly influence the accuracy of implant placement at the apex and angulation (P>.05) (Table 4).

In the FHIS group, 1 implant failed to osseointegrate and was removed 3 months after surgery. The other implants all successfully osseointegrated. Pain was

Table 3. Mean ±standard deviation implant accuracy between sa-RASS and FHIS group

Measurements		FHIS	sa-RASS	*P*
Platform Deviation (mm)	Global	1.46 ±0.86	0.93 ±0.50	.008
	Lateral	1.16 ±0.76	0.72 ±0.40	.016
	Depth	0.68 ±0.68	0.51 ±0.42	.372
	Excessive Depth	0.55 ±0.52 (n=14)	0.47 ±0.39 (n=17)	.905
Apex Deviation (mm)	Global	2.05 ±1.16	1.07 ±0.63	<.001
	Lateral	1.80 ±1.15	0.89 ±0.48	<.001
	Depth	0.70 ±0.70	0.53 ±0.53	.281
	Excessive Depth	0.49 ±0.45 (n=14)	0.45 ±0.37(n=17)	>.999
Angular Deviation (degrees)		7.93 ±3.55	3.10 ±1.68	<.001

Excessive Depth, implant placed apically deeper than planned position; FHIS, freehand implant surgery; sa-RASS, semi-autonomous robotic-assisted surgical system;

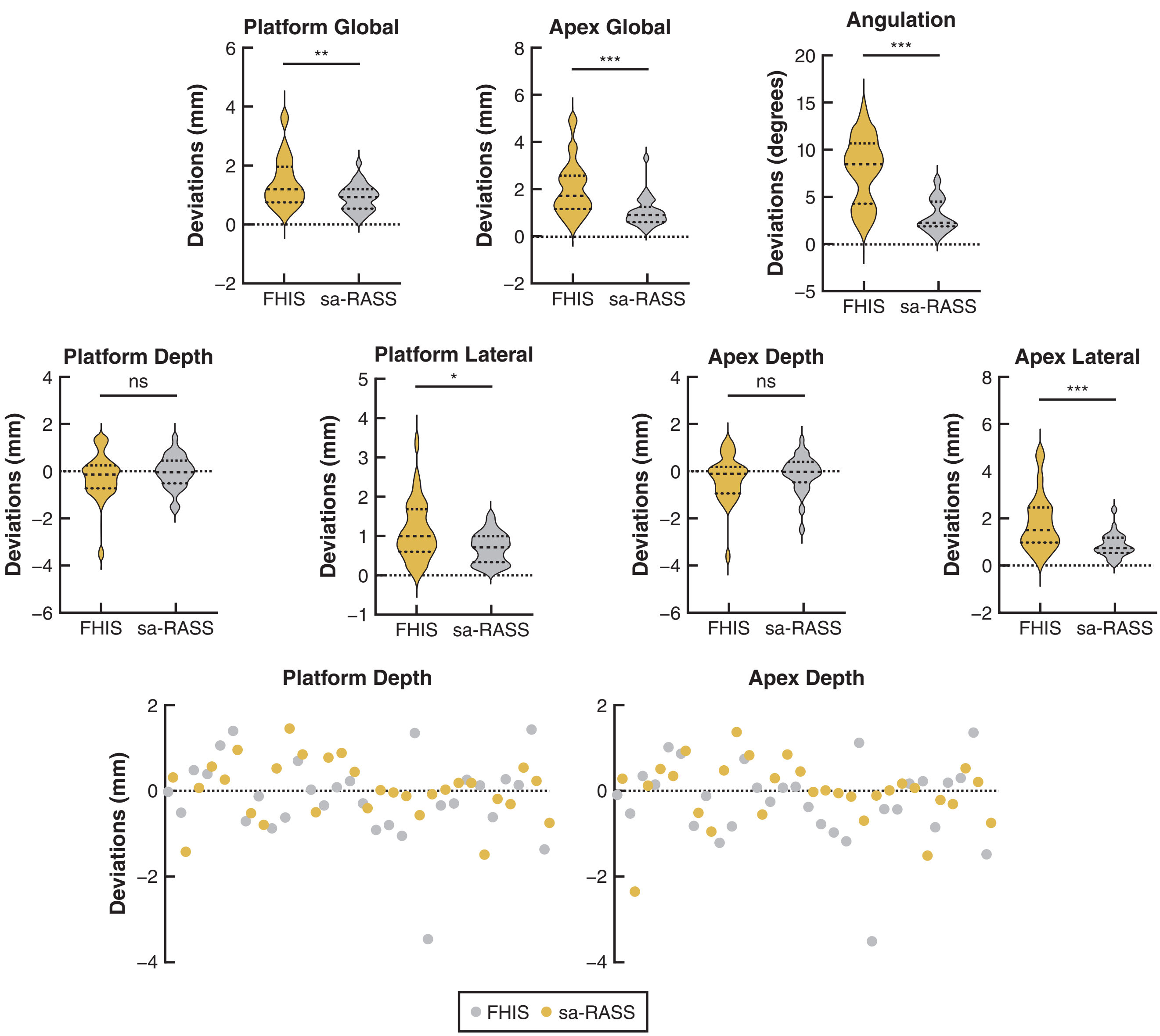

Figure 8. Comparison of deviations in implant platform, apex and angulation between sa-RASS and FHIS groups. FHIS, freehand implant surgery; sa-RASS, semi-autonomous robotic-assisted surgical system.

reported 1 day postoperatively in 7 participants from the FHIS group and 4 from the sa-RASS group, resolving within a day. Self-reported VAS pain scores are shown in Table 5. No other complications, such as intraoperative hemorrhage, injuries to adjacent structures, or implant displacement beyond the apical anatomic limit, were

Table 4. Linear regression analysis with statistically significant variables

	R^2	Unstandardized Coefficients		Standardized Coefficients	*t*	*P*
		B	Standard Error	Beta		
Platform Global Deviation	0.249					
Age		0.016	0.008	0.270	2.144	.037
Platform Lateral Deviation	0.347					
Age		0.020	0.006	0.369	3.147	.003
Group (FHIS / sa-RASS)		0.499	0.182	0.391	2.746	.008
Bone Density (D3/D2)		0.548	0.265	0.363	2.068	.044
Apex Global Deviation	0.312					
Group (FHIS / sa-RASS)		0.778	0.305	0.373	2.550	.014
Apex Lateral Deviation	0.323					
Group (FHIS / sa-RASS)		0.814	0.284	0.416	2.865	.006
Angular Deviation	0.492					
Group (FHIS / sa-RASS)		4.662	0.917	0.639	5.084	<.001

FHIS, freehand implant surgery; sa-RASS, semi-autonomous robotic-assisted surgical system.

Table 5. VAS scores of pain after surgery (median, interquartile range)

Group	Immediately	1 day	2 days	3 days	4 days	5 days	6 days	7 days
sa-RASS	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
FHIS	0 (0.50)	0 (0.25)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

FHIS, freehand implant surgery; sa-RASS, semi-autonomous robotic-assisted surgical system.

observed. The surgeon (Y.F.) expressed satisfaction with the overall operational safety of the sa-RASS, indicating no malfunctions, stability concerns, or negative incidents associated with the robotic system.

DISCUSSION

This study supports the hypotheses that the sa-RASS demonstrates operational feasibility, safety, and high accuracy in implant placement and achieves greater accuracy compared with freehand. The authors are unaware of a previous translational study to demonstrate a semi-autonomous implant robot from the model test to animal experiment and clinical applications. The sa-RASS significantly improved the accuracy of implant placement compared with freehand and showed high clinical operational feasibility and safety.

The first hypothesis, that the sa-RASS demonstrates operational feasibility and high accuracy in implant placement during the model test and animal experiment, was not rejected. This robotic implant surgical system combines the physical constraint advantage of static guides with the real-time display ability of dynamic navigation, enhancing accuracy and stability.[13,23] Unlike traditional navigational surgery, the sa-RASS does not require constant screen monitoring to adjust the handpiece, reducing operator fatigue and the potential for missed details.[10] Moreover, the sa-RASS can also automatically track and adjust the position of the handpiece with the patient's head movements, improving the accuracy of implant placement. In the preliminary model test Stage 1, there were larger implantation deviations than in Stage 2 when the sa-RASS was without this function. In the animal experiment, the deviation data of the platform and apex fell within the accepted range for static guides (mean deviation of 1.12 mm at the implant entry point and mean deviation of 1.39 mm at the apex), which has been generally considered to be highly accurate in clinical applications and which proves the high accuracy and clinical applicability of the sa-RASS.[1]

The second hypothesis, that the sa-RASS achieves higher accuracy compared with freehand, was also supported. In this study, the sa-RASS group showed smaller deviations in platform, apex, and angulation compared with the freehand group, indicating better implant placement accuracy. Although the semi-autonomous robot achieved good accuracy in both model test Stage 2 and the animal experiment, it exhibited larger angular deviations in the clinical application. The larger angular deviations may have been because of the complexities encountered clinically, such as the swallowing movement of the patient and limited oral operative space.[23] Nevertheless, the model studies indicated that the semi-autonomous robot still had smaller angular deviations than freehand or navigation.[11,12,17] In this study, no significant differences were found between the sa-RASS and freehand techniques in global depth deviation or excessive depth, indicating that even when using semi-autonomous robots for implantation, the safety margin for implant depth must still be considered.

In the linear regression analysis, the surgical group was the primary influencing factor in accuracy. The sa-RASS significantly impacted angular deviation compared with freehand. Age also affected the accuracy of the platform deviation, possibly because the alveolar bone shrinks with age, leading to a narrow width of the alveolar bone, which caused some deviation during the osteotomy procedure.[13,19,22] High bone density may have an impact on the lateral deviation of the platform, while low bone density may have affected the apex depth deviation.[29–31] The reason may be that, although the axial direction of the apex received sa-RASS control during the implant placement, the depth deviation may be more likely in the low-bone area with less resistance because of the non-rigid connection between the implant and the handpiece. In addition, other factors did not significantly affect implant placement accuracy, indicating the high stability and accuracy of the sa-RASS in different clinical scenarios.

This study provided positive support for the research on the accuracy and maneuverability of semi-autonomous robot, but there are some limitations. Prospective or retrospective studies with larger sample sizes are necessary to analyze potential complications or the factors that may affect the accuracy of the sa-RASS. Another limitation of this study related to the methods used to measure postoperative accuracy. At present, the most effective method of assessing postoperative accuracy is digital intraoral scanning, which avoids additional radiation exposure.[32] In the future, research on semi-autonomous robots will still have a number of potential challenges and issues that need to be addressed. First, the system can be further customized for different oral conditions and the special needs of different patient populations and second, standardized semi-autonomous robotic implant placement protocols (selection of drills, methods, and sequences) will need to be developed.

CONCLUSIONS

Based on the findings of this study, the following conclusions were drawn:

1. The sa-RASS demonstrates high accuracy for single-tooth implant placement, with high operational feasibility, safety, and low surgical morbidity.
2. The sa-RASS achieves higher accuracy compared with freehand ($P<.01$).
3. Bone density affected the deviation of the lateral platform ($P<.05$) and depth apex ($P<.05$), while age affected only the platform deviation. Age, sex, bone density, implant position, implant diameter, and length do not significantly affect the accuracy of implantation at the apex and angulation ($P>.05$).

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Acknowledgments
The authors thank Yucheng Zheng (Department of Stomatology, Zhejiang Provincial People's Hospital), Chengzhi Dong, Qingwei Tang, Zhuoheng Xia (College of Stomatology, Zhejiang Chinese Medical University), Xulan Yang, Chao Cheng, and Mijia Dai (Hangzhou Jianjia Medical Technology Company) for their assistance.

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Fan Yang: Conceptualization, Design, Formal analysis, Writing - original draft, Writing - review and editing. **Jianping Chen**: Methodology, Formal analysis, Writing - review and editing. **Linhong Wang**: Project administration, Formal analysis, Conceptualization, Validation, Writing - original draft. **Yude Ding**: Conceptualization, Formal analysis, Writing - original draft, Writing - review and editing.

https://doi.org/10.1016/j.prosdent.2024.10.026