BMC Oral Health

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Accuracy of robotic-assisted surgery for immediate implant placement in posterior teeth: a retrospective case series

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Abstract

Background Robotic computer-assisted implant surgery (r-CAIS) is a revolutionary innovation in oral implantation; however, the clinical feasibility of r-CAIS for immediate implant placement (IIP) in posterior teeth has not been verified. Thus, this study aimed to evaluate the accuracy of r-CAIS for IIP in posterior tooth regions.

Methods Patients with posterior teeth to be extracted and indicated to undergo r-CAIS were evaluated. The patients had positioning markers installed in the oral cavity and underwent cone-beam computed tomography (CBCT). Subsequently, minimally invasive tooth extractions were performed, and an individualised surgical plan was generated in the robotic software. After marker registration, implantation surgery was performed by the robotic arm under the supervision and assistance of the surgeons. Finally, the deviations between the planned and placed implants were evaluated based on preoperative and postoperative CBCT data.

Results A total of 12 patients were evaluated. No adverse events occurred during the surgery. The mean global coronal, global apical, and angular deviations were 0.46 ± 0.15 mm (95%CI:0.36 to 0.56 mm), 0.46 ± 0.14 mm (95%CI:0.37 to 0.54 mm), and 1.05 ± 0.55° (0.69 to 1.40°), respectively.

Conclusions Under the limited conditions of this study, the r-CAIS exhibited high accuracy in posterior teeth IIP surgery. Further multicentre randomised controlled studies are required to confirm the feasibility of this technology.

Keywords Accuracy, Immediate implant placement, Computer-assisted, Robotic surgical procedures, Posterior teeth

Background

Immediate implant placement (IIP) surgery is performed within a newly formed alveolar socket. IIP has received significant attention owing to its potential to minimise surgical trauma and frequency, shorten treatment duration, and enhance patient satisfaction [1]. Given that the accuracy of implant placement is crucial to aesthetic outcomes and long-term biological stability [2–6], one of the main challenges in IIP is to obtain an ideal three-dimensional position in the post-extraction alveolar socket [7, 8]. Currently, IIP is predominantly applied in anterior teeth, with relatively limited studies in posterior teeth owing to their intricate alveolar morphology and special

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surrounding anatomical structure [9–11]. Freehand implantation is susceptible to significant deviations in IIP, thus, the ITI consensus report suggested that such surgery should be performed by experienced surgeons [12].

However, the accuracy of IIP has greatly improved with the development of computer-assisted surgery technologies. These technologies mainly include static computer-assisted implant surgery (s-CAIS), dynamic computer-assisted implant surgery (d-CAIS), and robotic computer-assisted implant surgery (r-CAIS). The surgical plan of s-CAIS is established based on the optical scan model of the missing tooth regions. Subsequently, an individualised surgical guide is printed to maintain the implant in the correct position [13–15]. A randomised controlled trial demonstrated that s-CAIS for IIP is associated with significantly higher accuracy than that with free-hand implantation, particularly regarding angular deviation (0.83±0.53° versus 6.09±3.23°) [7]. Meanwhile, d-CAIS is not affected by the surgical guide plates. A prospective study indicated that both s-CAIS and d-CAIS achieved comparable accuracy for IIP in anterior teeth, with a global entry, apex, and angular deviation of 0.99±0.63 mm versus 1.06±0.55 mm, 1.50±0.75 mm versus 1.18±0.53 mm, and 3.07±2.18° versus 3.23±1.67°, respectively [16]. In addition, digital technologies have been applied to IIP in posterior teeth in several studies. A recent retrospective study evaluated the accuracy of free-hand IIP compared with that of s-CAIS- and d-CAIS-aided IIP in mandibular posterior teeth. The results demonstrated that the two digital technologies had significantly higher accuracy than that of free-hand implantation. d-CAIS showed higher accuracy than that of s-CAIS with respect to the root and angle deviations (0.52±0.13 mm versus 1.33±0.42 mm and 0.88±0.45° versus 1.77±0.30°, respectively) [17].

However, there are also some limitations in applying s-CAIS and d-CAIS for IIP. For example, s-CAIS entails prefabrication of the surgical guide, thus leading to additional visits. Further, the design plan cannot be changed intraoperatively [3, 15]. In addition, the gaps between the drills and metal sleeves can induce surgical errors [18, 19]. Similarly, in d-CAIS, frequent shifts in sight from the computer screen to the surgical region increase the probability of missing vital details in IIP [20–23], possibly increasing surgical errors. These deficiencies are further exacerbated by the intricate anatomy and restricted mouth opening in the posterior tooth regions.

The advent of r-CAIS marks a revolutionary innovation in oral implantation and has thus received increasing attention from researchers [21, 24–26]. r-CAIS exhibited lower deviations (entry, 0.81 mm; apex, 0.77 mm; and angular, 1.71°) compared to those with s-CAIS and d-CAIS in a meta-analysis of 67 studies [27]. This was validated to be a considerable advantage in IIP. However, most studies on r-CAIS for IIP are currently performed based on in vitro experiments [28, 29]. Despite being a promising technology, there are limited clinical studies available. A recent clinical study of r-CAIS for IIP demonstrated favourable accuracy in global platform, apex, and angular deviations (0.75±0.20 mm, 0.70±0.27 mm, and 1.17±0.73°, respectively) [8]. However, only the maxillary anterior teeth were included. The feasibility of r-CAIS for IIP in posterior teeth still needs to be verified in more clinical studies.

Therefore, this retrospective study aimed to evaluate the accuracy of r-CAIS for IIP in posterior teeth. Towards this goal, we assessed the deviation between the planned and placed implants.

Methods

Study design and population

This study presented a retrospective case series of r-CAIS for IIP in posterior teeth. The study protocol was approved by the local Ethics Committee (Number: 202412 A). The patients were identified from the specialised records of the Department of Implant Dentistry. Only patients who underwent immediate posterior teeth implantation surgery with the Remebot robotic system (Baihui Weikang, Beijing, China) between June 2023 and May 2024 were included.

The inclusion criteria were as follows: (1) presented with a posterior tooth which was determined to be non-restorable following multidisciplinary consultation; (2) age≥18 years; (3) good general health and oral hygiene; (4) no acute systemic or local inflammation; (5) good mouth opening (>30 mm); (6) no smoking or light smoking (<10 cigarettes/day); and (7) good treatment compliance.

The exclusion criteria were as follows: (1) uncontrolled systemic or psychiatric diseases; (2) uncontrolled periodontal disease; (3) general contraindications for IIP; (4) pregnancy or lactation; (5) heavy smoking (>10 cigarettes/day) or alcoholism; and (6) severe bruxism or clenching.

r-CAIS workflow

The workflow of r-CAIS was divided into the preoperative, intraoperative, and postoperative phases, as illustrated in Fig. 1a.

Preoperative phase

The robotic system was verified and adjusted preoperatively (Fig. 1b) to ensure normal operation of both hardware and software. The patients were instructed to rinse their mouth with 0.12% chlorhexidine solution for 3 min. A universal positioning marker with seven ceramic balls (Baihui Weikang, Beijing, China, as shown in Fig. 2a) was attached to the opposite tooth regions of the surgical

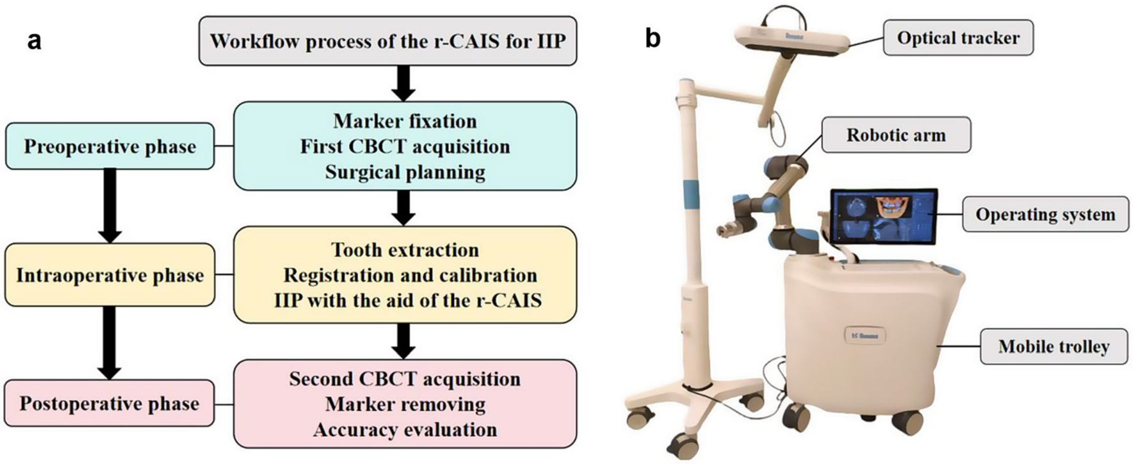

Fig. 1 Treatment protocol and robotic system. (**a**) Workflow process of r-CAIS for posterior teeth IIP. (**b**) The robotic system consists of an optical tracker, a robotic arm, an operating system, and a mobile trolley. *IIP* immediate implant placement; *r-CAIS* robotic computer-assisted implant surgery

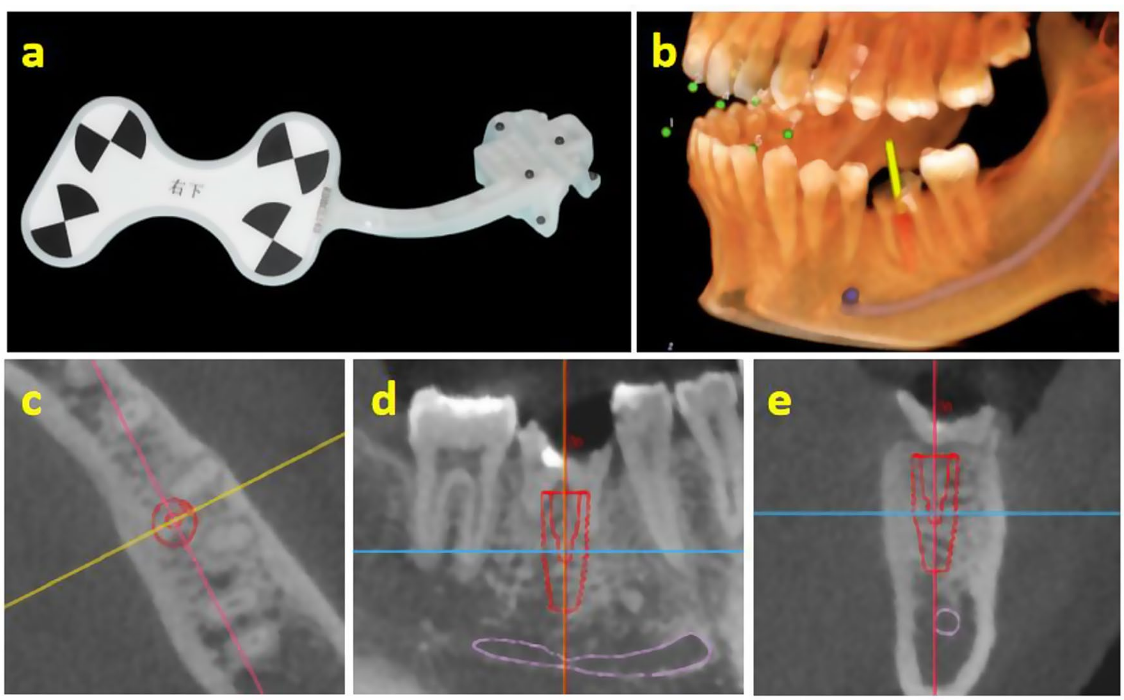

Fig. 2 Preoperative phase of case VII. (**a**). Universal positioning marker. (**b**) 3-dimensional image of the surgical area. (**c**-**e**). Transverse, coronal, and sagittal plane of the preoperative design

area (generally canines and premolars). Subsequently, the self-curing acrylic resin (Protemp™, 3 M ESPE, Neuss, Germany) was injected into the marker, gently placed on the target tooth regions, and fixed with fingers until it solidified. Then, the patients underwent preoperative cone-beam computed tomography (CBCT, KAVO, Biberach, Germany) with parameters of 120 kV/1.38 mA, 0.25 mm voxel size, and 26.9 s scanning time. The Digital Imaging and Communications in Medicine (DICOM) format data file was transferred to the robotic software (RemebotDent, Baihui Weikang, Beijing, China), and the three-dimensional image of the surgical area was reconstructed. Finally, a preoperative surgical plan was generated according to the design principles for IIP, as illustrated in Fig. 2b-e.

Intraoperative phase

After intraoral and extraoral disinfection, local anaesthesia with Primacaine® (4% Articaine, 1:100,000 adrenaline, ACTEON, M´erignac, France) was applied to the operative region. To minimise surgical trauma and preserve the bone wall integrity, tooth extraction procedures were performed with a series of minimally invasive tooth elevators. If the preoperative evaluation of the tooth extraction was relatively difficult, dental drills (KOMET, Besigheim, Germany) with a high-speed dental handpiece were used to help segment teeth in pieces. The integrity of the alveolar fossa was examined preoperatively. The robotic arm (Universal Robots, Odense, Denmark) was registered and calibrated with the positioning marker. Subsequently, the surgeon moved the robotic arm near the surgical area and completed the implant osteotomy with r-CAIS (Fig. 3a, b). The whole process of the surgical real-time feedback screen was recorded (Fig. 3c). The surgeon could check the axial direction after each step and correct the surgical plan as needed throughout the implantation procedure. The positioning marker was promptly removed following the completion of implant placement. Subsequently, the gap between the implant and bony plate was filled with the bone substitute material (Bio-oss, Geistlich, Wolhusen, Switzerland). The insertion torque value was measured using a dynamometric wrench to assess primary stability. If the insertion torque exceeded 15 N.cm, a healing cap with appropriate diameter and height was installed; if it was below 15 N.cm, the covering screw was placed. The wounds were finally sutured with 5−0 polypropylene nonabsorbable sutures (Ethicon, Johnson & Johnson, New Jersey, United States). The surgical procedure images were shown in Fig. 4.

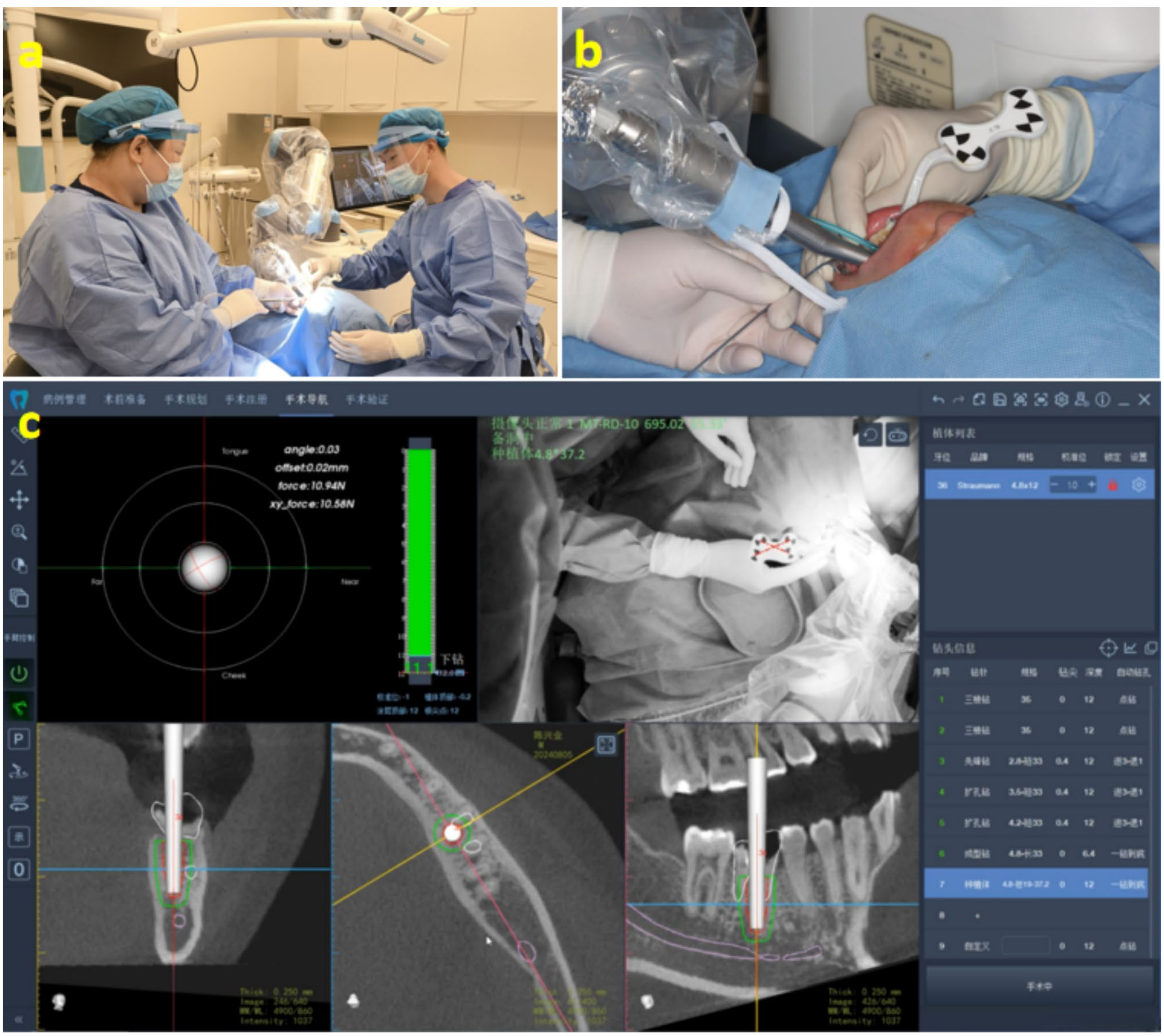

Fig. 3 Image of the intraoperative phase of case VII. (**a**) Robot-assisted surgery. (**b**) The implant osteotomy was automatically performed by the robotic surgery system. (**c**) Real-time computer screen of the robotic system software

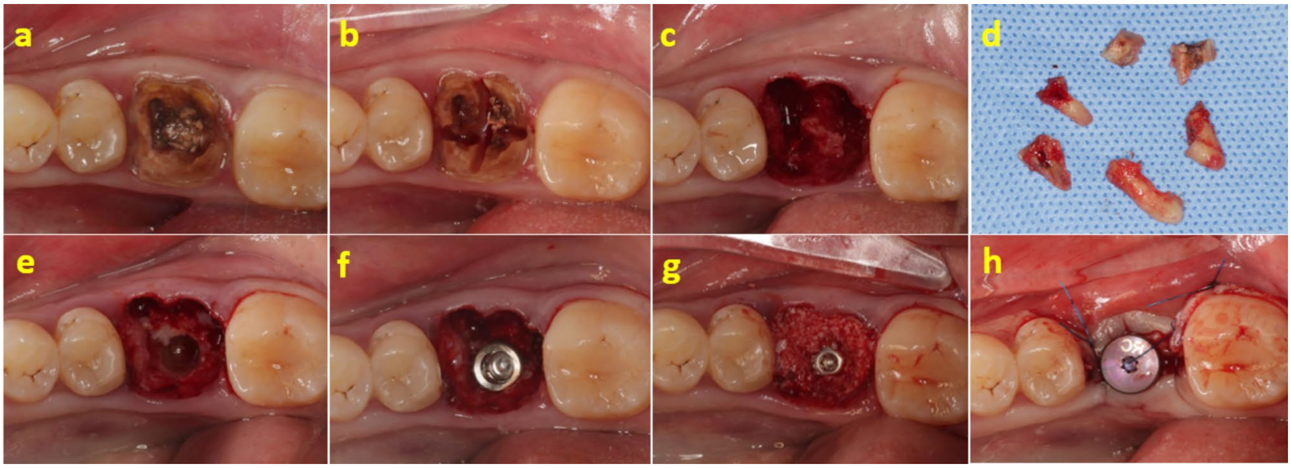

Fig. 4 Surgical procedure images of case VII. (**a**). Preoperative image. (**b**). Molar residue crown was segmented into four pieces. (**c**). The post-extraction alveolar socket. (**d**). Extracted tooth. (**e**). The robot-assisted implant cavity preparation. (**f**). The robot-assisted implant placement. (**g**). Bone graft in the gap between the implant and bony plate. (**h**). Position the healing cap and suture

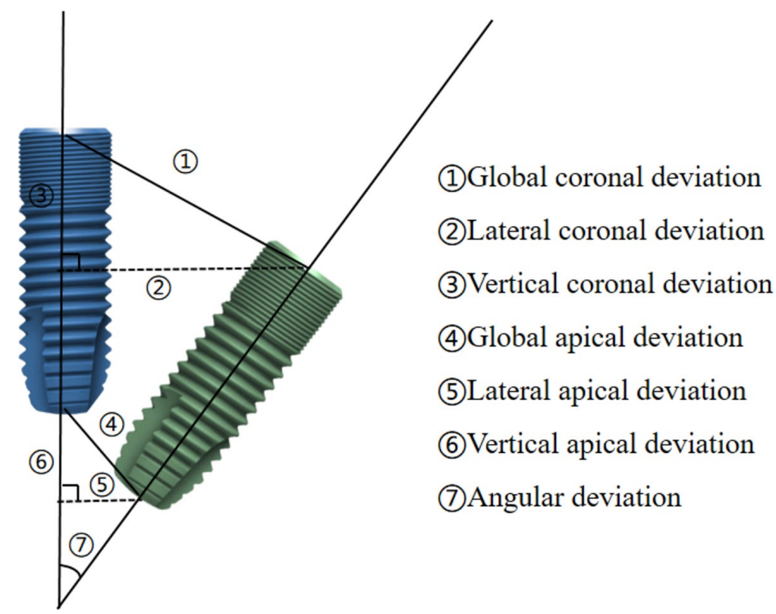

Fig. 5 Graphical representation of the deviations between the planned and placed implants

Postoperative phase

Postoperative instructions

Postoperatively, the patients were given instructions about precautions and medications. Particularly, the patients were instructed to rinse their mouth with 0.12% chlorhexidine solution twice daily for 5 days; they were also prescribed oral systemic antibiotics (0.25 g cefuroxime, twice daily for 3 days) and analgesics (0.4 g ibuprofen tablets, twice daily as needed). Penicillin-allergic patients were prescribed 300 mg roxithromycin twice daily for 3 days. Sutures were removed 10–14 days postoperatively.

Accuracy analysis

Each patient underwent postoperative CBCT. Subsequently, the two DICOM format files were merged in the surgical verification software (Remebot, Baihui Weikang, Beijing, China), and the deviations between the planned and placed implants were analysed according to previously described methods [30–32]. Finally, based on the central axis of the planned and placed implants (Fig. 5), the robotic software generated an accuracy analysis report, including the coronal (global, lateral, and vertical) and apical (global, lateral, and vertical) deviations in millimetres and the angular deviation in degrees.

Statistical analysis

The quantitative data are presented as standard descriptive statistics, including means, standard deviations, maximums, minimums, and upper/lower 95% confidence intervals (CIs). The normality of variable distribution was evaluated using the Shapiro–Wilk test ($\alpha=0.05$). All statistical analyses were performed using SPSS 23.0 software (IBM Corp., New York, United States).

Results

Patient characteristics

A total of 12 patients aged 23–60 (mean: 37.2±10.4 years) were included. No intraoperative or postoperative advents were reported, and all patients underwent IIP surgery. Table 1 presents the demographic and surgical data of the patients. The molar and premolar sites were involved in eight and four patients, respectively. The number of maxillary and mandible teeth was three and nine, respectively. Five implants were cylindrical, and the other seven were conical, ranging from 3.6 to 4.8 mm in diameter and 9 to 12 mm in length. The insertion torque varied from 25 to 45 N.cm.

Accuracy

Figure 6 shows the pre- and postoperative fusion images. The quantitative outcomes are listed in Table 2. The mean global coronal, global apical, and angular deviations were 0.46±0.15 mm (95%CI:0.36 to 0.56 mm), 0.46±0.14 mm (95%CI:0.37 to 0.54 mm), and 1.05±0.55° (0.69 to 1.40°), respectively. All data conformed to a normal distribution based on the Shapiro–Wilk test ($P>0.05$). Figure 7 shows the results of the global coronal, global apical, and angular deviations for each case.

Discussion

This study showed that r-CAIS can be a promising modality for immediate posterior teeth implantation. The mean global coronal and apical deviations were less than 0.5 mm, and the mean angular deviation was nearly 1°. To the best of our knowledge, this study is the first case series on r-CAIS for IIP in posterior teeth.

r-CAIS addresses the limitations of s-CAIS and d-CAIS, showing high accuracy in previous studies [30, 31, 33]. Currently, r-CAIS for IIP is mainly focused on anterior teeth. In an in vitro study, r-CAIS showed higher apical and angular accuracy in anterior IIP than did d-CAIS (0.77±0.34 mm versus 0.95±0.38 mm and 1.94±0.66° vs. 3.44±1.38°, respectively) [29]. Another retrospective clinical study demonstrated that the immediate anterior implantation accuracy was higher with r-CAIS than with s-CAIS [33]. Our results were comparable with the findings of these studies, which may be mainly attributed to the excellent stability of the robotic arm [29]. Although s-CAIS and d-CAIS provide navigation for surgeons, both technologies require manual control of the implantation handpiece, which would inevitably cause jittering and lead to side shifting, and are thus highly dependent on the surgeons' experience [22, 34, 35]. However, a robotic arm can well maintain the orientation and angle when encountering the pressure from the inclined plane of the bone wall. On the one hand, the repetition accuracy of the robotic arm is 0.033 mm, enabling accurate and efficient implementation of the preoperative surgical design [30]. On the other hand, the robotic arm has a 0.06-s follow-up function (provided by the manufacturer), allowing for an instantaneous adjustment of the drill direction to return to the planned direction after micromovement of the patients [28].

IIP in posterior teeth presents greater challenges owing to the surrounding important anatomical structures and the substantial difference in bone density between the upper and lower jaws [10, 17, 36]. The bone mass in the maxillary posterior regions are generally class III–IV types. Meanwhile, owing to the existence of the maxillary sinus, the available bone height on the palatal side is usually limited. Therefore, it is more difficult to achieve good

Table 1 Demographic and surgical characteristics of patients

Patient No.	Age	Sex	Site	Region	Implant type	Implant geometry	Implant size	Insertion Torque (*N*.cm)
I	36	F	15	premolar	Straumann BLT	conical	4.1×12	35
II	32	M	16	molar	Astra EV	cylindrical	4.2×9	25
III	60	F	25	premolar	Astra EV	cylindrical	3.6×11	30
IV	35	M	35	premolar	Astra EV	cylindrical	3.6×11	45
V	53	F	35	premolar	Astra EV	cylindrical	4.2×11	45
VI	39	F	36	molar	Straumann BLT	conical	4.8×12	35
VII	29	M	36	molar	Straumann BLT	conical	4.8×12	35
VIII	39	M	36	molar	Astra EV	cylindrical	4.8×11	35
IX	23	F	36	molar	Straumann BLT	conical	4.8×12	25
X	27	F	37	molar	Straumann BLT	conical	4.8×10	30
XI	34	M	37	molar	Straumann BLT	conical	4.8×12	35
XII	40	M	47	molar	Straumann BLT	conical	4.8×12	35

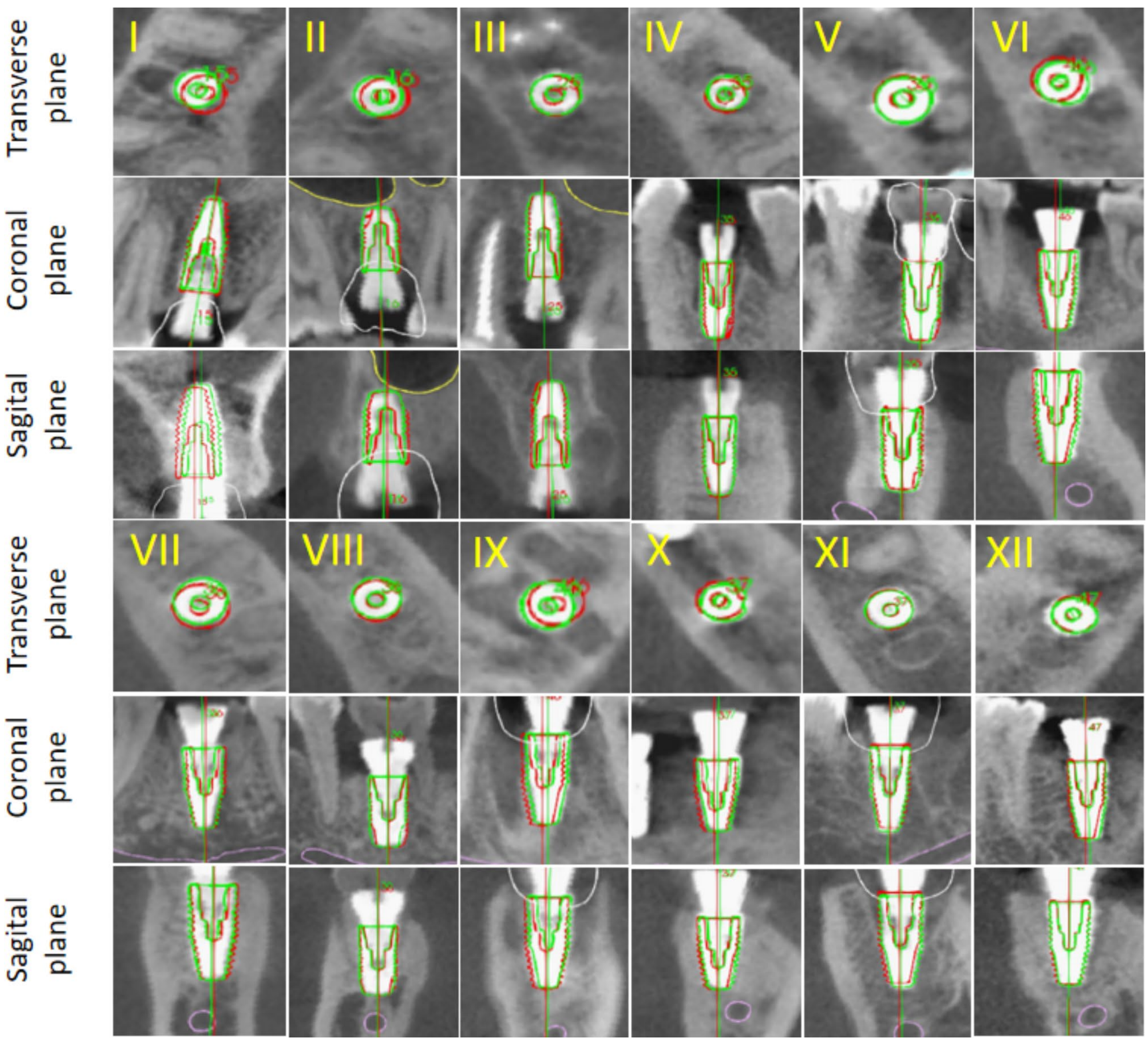

Fig. 6 CBCT fusion images of planned and placed implants for each case. Planned implants are outlined by red and placed implants by green. *CBCT* cone-beam computed tomography

Table 2 Descriptive statistics of implant deviations

Deviation	Mean	Standard deviation	Max	Min	Median	Lower 95% CIs	Upper 95% CIs	Shapiro-Wilk test
Global coronal deviation (mm)	0.46	0.15	0.80	0.26	0.45	0.36	0.56	0.61
Lateral coronal deviation (mm)	0.39	0.17	0.71	0.15	0.39	0.28	0.50	0.82
Vertical coronal deviation (mm)	0.09	0.21	0.48	-0.20	0.04	-0.04	0.23	0.71
Global apical deviation (mm)	0.46	0.14	0.76	0.27	0.44	0.37	0.54	0.76
Lateral apical deviation (mm)	0.40	0.12	0.66	0.23	0.40	0.32	0.48	0.79
Vertical apical deviation (mm)	0.09	0.21	0.48	-0.20	0.04	-0.04	0.23	0.68
Angular deviation (∘)	1.05	0.55	2.06	0.12	0.97	0.69	1.40	0.98

CIs confidence intervals

initial stability for IIP in the maxillary posterior regions. IIP in this region may even combine with a maxillary sinus elevation, which increases surgical risks [37]. However, with r-CAIS, the remaining bone can be maximised to ensure sufficient primary stability and reduce surgical risks. As depicted in Fig. 6 (cases I, II), dental implants were placed in the posterior maxilla with the implant apex close to the bottom of the maxillary sinus and the

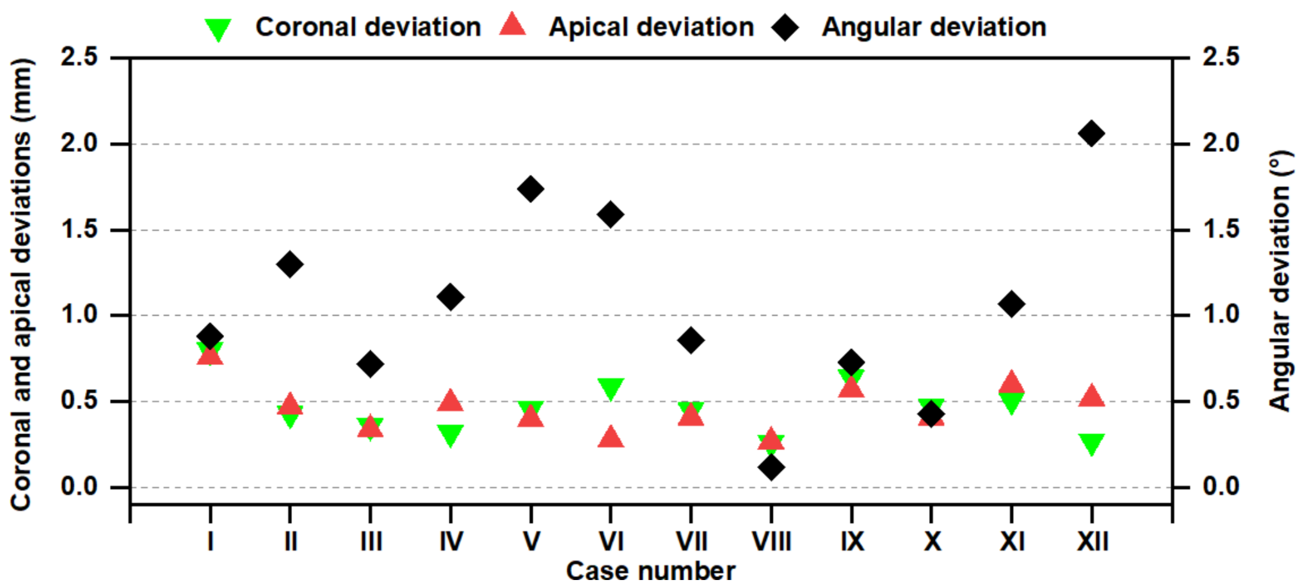

Fig. 7 Global coronal, apical, and angular deviations for each case. The coronal, apical, and angular deviations are outlined by green triangles, red triangles, and black rhomboids, respectively

insertion torque more than 15 N.cm. In addition, in the posterior mandible, although longer implants are required in IIP to achieve favourable primary stability, a safe distance of 2 mm is recommend to be left to reduce the risk of nerve damage (mental foramen and inferior alveolar canal) [37].

In this study (cases V–XII), the neural tubes were marked out in the robotic software to monitor the safe distance intraoperatively, thus ensuring the safety of the surgery. In addition, as shown in Table 2, the mean vertical apical deviation (0.09 mm) was lower than the mean lateral apical deviation (0.40 mm), indicating that r-CAIS has better depth control. This finding is consistent with those of many other studies [8, 21, 31, 38], which may be due to the real-time depth monitoring of the robotic software, allowing the operator to more clearly perceive the depth of implantation. Therefore, further research on the vertical deviation in r-CAIS may potentially lead to the reduction of the traditional 2-mm safe distance threshold [30].

In addition, the classification of sagittal root position and angulation of premolars is complicated [37]. If IIP cannot be completed with high precision in accordance with the preoperative design in maxillary or mandibular premolars, this may lead to perforation of the maxillary sinus or lingual plate [10, 36]. Moreover, the molar regions are usually composed of a multi-rooted alveolar fossa characterised by an irregular shape, making it challenging to obtain favourable implantation position and primary stability [17, 39]. The presence of an interradicular septum may lead to continuous drill slippage, resulting in inaccurate implant placement [40]. However, with r-CAIS, we conducted a preoperative implantation simulation, during which the stable robotic arm efficiently implemented the procedure, thereby reducing the incidence of similar complications. Currently, there is no in vitro or in vivo study on r-CAIS for IIP in the molar regions. Our study included eight cases involving the molar regions (cases II, VI to XII; Fig. 7), and the results showed high accuracy, with the coronal, apical, and angular deviations ranging from 0.26 to 0.64 mm, 0.27 to 0.6 mm, and 0.12 to 2.06°, respectively.

The results were comparable with those of similar studies focused on d-CAIS or s-CAIS for posterior teeth IIP [17, 40]. The limited data indicated that r-CAIS for IIP had a potential to be applied in posterior teeth, even in challenging molar regions. The limited inter-arch space in the molar regions presents a greater challenge for applying traditional digital technologies such as s-CAIS [40]. However, without the restraint of the surgical guide, r-CAIS can even be performed in the second molar regions. Moreover, r-CAIS can be switched to manual mode (like d-CAIS), allowing the robotic arm to rotate and tilt freely into the surgical area before reverting to automatic mode. As shown in Fig. 6 (cases X to XII), IIP was performed with high accuracy in second mandibular molars with the aid of the robotic arm.

In the current study, the deviation analysis images suggested that most deviations were placed slightly away from the inclined bone wall with reference to the preoperative designs (Fig. 6). Other anterior IIP studies also indicated that with the resistance of the palatal bone wall, r-CAIS for anterior IIP could not eliminate labial deviations [8, 28, 29]. Owing to the resistance of the slanted bone wall and the micro-movement of patients when experiencing the pressure from the drills, we recommend that the planned implant be slightly moved into the slanted bone wall in the surgical design to offset its displacement from bone resistance. Additionally, a sharp drill with good lateral cutting force for the initial step should be used to minimise drill sideslip intraoperatively, as it offers high cutting efficiency and facilitates easy penetration of the hard bone. Similarly, a round bur with a sharp cutting edge can also be used to prepare a stable approach for subsequent drill entry [8].

The key advantage of r-CAIS is in its superior precision, but there are also some disadvantages in its application for IIP in the posterior tooth regions. First, teeth extraction is required, and the marker should be installed in the correct area to avoid interference with related surgical procedures under limited mouth opening. Second, a relatively extended surgical duration is required owing to several steps such as CBCT data acquisition and transmission, marker installation and removal, and robotic arm registration and calibration. This will increase patient discomfort, posing challenges to the implementation of r-CAIS, especially in more complicated posterior teeth IIP.

The results of this retrospective study demonstrated that r-CAIS could achieve high accuracy for IIP in posterior teeth. Nevertheless, some limitations should be noted. First, this was a retrospective case series without a comparative cohort. Hence, s-CAIS and d-CAIS should be compared as control groups in future randomised controlled trials. Moreover, only CBCT was utilised for accuracy assessment; non-radiological evaluation techniques, such as dental magnetic resonance imaging [41] and intraoral scanning [42], should be considered in the future to minimise the radiation exposure and potential harm to the patients. Lastly, this study only reported the accuracy of r-CAIS for posterior teeth IIP. Patient satisfaction and long-term biological outcomes were not evaluated. These parameters should be investigated in further clinical studies.

Conclusions

Within the limitations of this study, it is possible to establish that r-CAIS for IIP can achieve high accuracy for specific posterior teeth either maxilla or mandible in this case series. Further large-scale multicentre randomised clinical studies are needed to verify this finding.

Abbreviations

IIP	Immediate implant placement
CBCT	Cone-beam computed tomography
s-CAIS	Static computer-assisted implant surgery
d-CAIS	Dynamic computer-assisted implant surgery
r-CAIS	Robotic computer-assisted implant surgery
DICOM	Digital Imaging and Communications in Medicine

Acknowledgements

The authors would like to acknowledge the excellent technical assistance of Dingjun Zhong from Beijing RuiYiBo Technology Co., Ltd.

Author contributions

Tao Yang: Writing – review & editing, Writing – original draft, Funding acquisition, Data curation, Conceptualization, Software.Wenan Xu: Writing – review & editing, Writing – original draft, Data curationXiaojian Xing: Writing – review & editing, Software, ConceptualizationFengzhou Li: Writing – review & editing, Validation, Supervision.Shuo Yang: Writing – review & editing, Methodology, Project administration.Buling Wu: Writing – review & editing, Supervision, Data curation, Funding acquisition, Project administration, Resources.

Funding

This study was supported by grants from Shenzhen Science and Technology Program (No: JCYJ20220530162408020) and the President Foundation of Shenzhen Stomatology Hospital (Pingshan), Southern Medical University (No:2022A001 and 2022C003).

Data availability

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

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of Shenzhen Stomatology Hospital (Pingshan) of Southern Medical University (Number: 202412 A) and followed the guidelines of the Declaration of Helsinki. All patients provided written informed consent after receiving detailed information about the treatment procedure and potential intraoperative and postoperative complications.

Consent for publication

No applicable.

Competing interests

The authors declare no competing interests.

Received: 7 August 2024 / Accepted: 17 October 2024
Published online: 22 October 2024

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