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Application of dental implant robots and conventional dental implants in oral implantology – a propensity score matching study

Примена денталних имплантационих робота и конвенционалних денталних имплантата у оралној имплантологији – студија заснована на подударању склоности

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Примена денталних имплантационих робота и конвенционалних денталних имплантата у оралној имплантологији – студија заснована на подударању склоности

SUMMARY

Introduction/Aim The aim of this study is to evaluate the application value of dental implant robot (DIR) in dental implant restoration of patients with tooth loss (TL), so as to provide reference for clinical practice.

Methods 47 patients with TL who received DIR oral implantation in our hospital during the period from March 2021 to August 2023 were selected as the research subjects. By propensity score matching (PSM), according to the ratio of 1:1, the nearest neighbor matching algorithm was used to select 47 patients who received conventional oral implantation as the control group. The matching variables included age, gender, history of diabetes, history of hypertension, location of missing teeth, cause of missing teeth, and number of missing teeth. To compare the implant errors of the two groups and to test their oral function after oral implantation. In addition, we investigated the patients' pain using the visual analogue scale (VAS) and assessed their aesthetic appearance. Finally, the incidence of complications in the patients was recorded.

Results Compared to the control group, the implant error was lower in the observation group ($p < 0.05$). After implantation, there was no difference in verbal expression and occlusal ability between the two groups ($p > 0.05$), but VAS was lower in the observation group than in the control group at one week and one month after surgery ($p < 0.05$). There was no difference in the complication rate between the two groups ($p > 0.05$), but the observation group had better aesthetic appearance.

Conclusion DIR effectively enhances the accuracy of oral implantation and ameliorates the aesthetic outcome for patients.

Keywords: robotics; treatment outcome; tooth loss; plantation accuracy; treatment outcome; oral implantation

САЖЕТАК

Увод/Циљ Циљ ове студије је проценити вредност примене робота зубних имплантата (ДИР) у обнови зубних имплантата пацијената са губитком зуба (ТЛ), како би се пружила референца за клиничку праксу.

Методе 47 пацијената са ТЛ-ом који су примили оралну имплантацију ДИР-а у нашој болници у периоду од марта 2021. до августа 2023. изабрани су као предмети истраживања. Усклађивањем резултата склоности (ПСМ), према односу 1: 1, алгоритам подударања најближег суседа коришћен је за избор 47 пацијената који су примили конвенционалну оралну имплантацију као контролну групу. Одговарајуће променљиве укључују старост, пол, историју дијабетеса, историју хипертензије, локацију зуба који недостају, узрок зуба који недостају и број зуба који недостају. Упоређивање грешака имплантата две групе и тестирање њихове оралне функције након оралне имплантације. Поред тога, истраживали смо бол пацијената користећи визуелну аналогну скалу (ВАС) и проценили њихов естетски изглед. Забележена је учесталост компликација код пацијената.

Резултат У поређењу са контролном групом, грешка имплантата била је мања у групи за посматрање ($p < 0,05$). Након имплантације није било разлике у вербалној експресији и оклузалној способности између две групе ($p > 0,05$), али ВАС је био нижи у посматрачкој групи него у контролној групи у недељи и месецу дана након операције ($p < 0,05$). Није било разлике у стопи компликација између две групе ($p > 0,05$), али посматрачка група је имала бољи естетски изглед.

Закључак: ДИР ефикасно повећава тачност оралне имплантације и побољшава естетски исход пацијената.

Кључне речи: роботика; исход лечења; губитак зуба; тачност плантаже; исход лечења; орална имплантација

INTRODUCTION

Tooth loss (TL) constitutes one of the highly prevalent oral diseases in clinical settings, predominantly affecting middle-aged and elderly patients. It can be induced by a multiplicity

of factors, including dental caries, various oral pathologies, or accidental trauma [1]. Statistically, the global incidence rate of TL ranges from approximately 23–53%, and this figure exhibits an upward trend year by year [2]. The onset of TL not only compromises the integrity of the dentition, resulting in occlusal dysfunction, alveolar bone atrophy, and decreased masticatory function, but also precipitates the development of other periodontal disorders [3]. The golden standard to treat TL is oral implantation, which involves the insertion of pure titanium implants into the alveolar bone to replace the absent teeth [4]. In recent years, with people's increasing attention to oral health and the advancement of medical technology, oral implantation technology has become more and more sophisticated and has currently become the preferred treatment option for more than 70% of TL patients [5]. The research focus of modern dental implant medicine centers on how to further curtail the surgical treatment duration, enhance patient comfort, and guarantee the success rate of the surgical procedure.

In 2016, the first dental implant robot (DIR) was granted approval for clinical medical application, presenting a brand-new solution for enhancing the accuracy and predictability of implant surgeries [6]. DIR works by using digital scanning and 3D reconstruction technology to accurately measure and analyze the patient's oral cavity, and then relies on a high-precision robotic arm to perform oral implants [7]. However, as a cutting-edge technology, the clinical application of DIR has received mixed reviews. For example, Dibart et al. [8] believe that the practical application ability of DIR is not yet sufficient to meet clinical needs, especially when dealing with complex anatomical conditions or when real-time decision adjustment is required. Li et al. [9] pointed out that the application of DIR needs more clear clinical evidence support, especially in terms of long-term success rate and cost-benefit ratio. These controversies highlight the need for further evaluation of DIR effectiveness and applicability in real clinical Settings. Secondly, due to the relatively stringent requirements of DIR regarding hospital facilities and the operational proficiency of surgeons, it has not yet achieved comprehensive

popularization throughout China. Related reports are usually reviews [10, 11], lacking of exact clinical studies.

Since 2020, our hospital has been engaged in the promotion of DIR usage within its premises. At present, a sufficient caseload has been amassed. In light of this situation, we conducted a retrospective analysis to verify the application value of DIR in oral implantation, thereby remedying the existing deficiency in DIR-related research in China. In view of the limited clinical application data of DIR, the aim of this study is to compare the differences between DIR-assisted oral implantation and traditional oral implantation in the treatment of TL through retrospective analysis, in order to provide reference and guidance for future clinical decision-making of oral implant treatment.

METHODS

Research subjects

Patients with TL who received oral implantation in Nanjing Stomatological Hospital during the period from March 2021 to August 2023 were selected as the research subjects for retrospective analysis. The PSAA software was used to calculate the required sample size based on the significance level $\alpha = 0.05$ (two-sided test) and statistical power $1-\beta = 0.8$. The expected effect size was set as [mean difference of apical error between the two groups was 0.6mm, standard deviation was 0.2mm]. In addition, we calculated that a minimum of 47 samples per group would be required to account for a 10% risk of dropout. The treatment options for the patients were either DIR-assisted implantation (observation group) or conventional dental implants (control group).

Inclusion and exclusion criteria

Inclusion criteria were: (1) Normal mouth opening and occlusal function, with no loosening of adjacent teeth. (2) Healthy gums, good bone density, and sufficient and intact thickness of the labial wall. (3) Good overall health status, with no contraindications for oral implantation. Exclusion criteria were: (1) Inability to tolerate the implantation surgery. (2) Presence of bad occlusal habits. (3) Refusal to accept regular follow-up. (4) Existence of communication disorders or mental illnesses.

Data collection

Patients' baseline data and clinical features were collected, including but not limited to the following variables: demographic data such as gender, age, smoking history, drinking history, and place of residence; clinical features like the location, quantity, and reason of TL. All data were extracted through the electronic medical record system to ensure the accuracy and integrity of the data.

Surgical approaches

Conventional dental implants: Preoperatively, patients were informed about the surgical workflow. Relevant laboratory and imaging examinations were carried out, along with an assessment of both the intra-oral and general health status. Additionally, the environment, equipment, and preparatory items in the operating room were introduced. Following routine disinfection and draping, local infiltration anesthesia was administered to the patient using articaine (1.7 mL). During the surgical procedure, the dental implantologist performed gingival

incision, flap reflection, sequential osteotomy for cavity preparation, implant placement, and wound suturing. Postoperatively, spiral CT scans were re-performed to evaluate the outcomes.

DIR: (1) Preoperatively, cone-beam computed tomography (CBCT) was performed to verify the patient's eligibility for implantation, and intra-oral scanning was conducted to obtain the dentition data (Figure 1A). The Digital Imaging and Communications in Medicine (DICOM) data of the CBCT and the Standard Template Library (STL) data of the intra-oral scan were then imported into the implant robot system. Through the system software, the position of the implant was designed, and the implantation path of the robot was planned (Figure 1B). Subsequently, an intra-oral positioning guide was fabricated, which was then connected to the calibration component to realize the spatial position relationship transformation between the robot and the intra-oral implantation site. Thereafter, the implantation steps were designed, and the corresponding sequential relationship between the selected tools and implantation steps was established to plan the implantation protocol. (2) After calibration, the osteotomy site was prepared. Drill bits were replaced according to the preset sequence for sequential cavity preparation. During the entire drilling process, the robotic arm was adjusted in real time to ensure that the implantation point, and the three-dimensional orientation of the implant were in accordance with the preoperative design (Figure 1C). (3) Under the instruction of the surgeon, the robotic implantation system completed the preparation of the implantation socket according to the preoperative plan. Depending on the patient's mouth-opening degree, the implant was either placed by the robot or manually (Figure 1D). (4) CBCT was repeated after surgery to confirm the results obtained (Figure 1E).

Follow-up for prognosis

All patients were subjected to a one-year prognostic follow-up investigation that was conducted regularly at two-month intervals. After one year, all implant restorations were completed, and the implant success rate was computed. The criteria for successful implantation were defined as follows: the implant remained stable with no evidence of loosening; X-ray examination revealed no radiolucent zones in the peri-implant bone tissue; and the patient reported a favorable condition without any abnormal sensations.

Outcome measures

(1) Based on the preoperative and postoperative CBCT scan results of patients, the apical point error and implant angle error between the preoperatively planned implant and the actual implant were measured. (2) The Chinese Language Articulation Test [12] was employed for patient assessment, with the score calculated as (the number of correctly articulated words/the total number of test words) × 100%. (3) The T-Scan computerized occlusal analysis system (Tekscan Inc., Norwood, MA, USA) was utilized to detect the pressure exerted by the dental implant during occlusion. Additionally, the percentage of pressure during occlusion with the contralateral homologous control tooth was recorded. (4) The Visual Analogue Scale (VAS) [13] was adopted to investigate the pain status (scored from 0–10) at the surgical site during the preoperative stage (T0), one week after the implantation (T1), one month after the implantation (T2), and six months after the implantation (T3). A higher score on the VAS indicated a more pronounced pain level. (5) One year after the implantation, the Pink Esthetic Score (PES) and the White Esthetic Score (WES) [14] were employed to evaluate the esthetic outcome. The PES includes seven parameters: mesial and distal papilla, labial gingival margin curvature and height, and root convexity, as well as soft tissue color and texture (with a total

score ranging from 0-14 points). The WES consists of five elements: crown color, crown shape, crown contour, crown surface texture, and crown transparency (with a total score ranging from 0-10 points). Higher scores in PES and WES signify enhanced esthetic outcomes following restoration. (6) The incidence of complications such as postoperative gingival inflammation, infection, and periodontal discomfort in patients was recorded. (7) The self-developed satisfaction survey scale of our hospital was utilized to evaluate patient satisfaction regarding this implant treatment. This scale encompasses dimensions including the medical environment, treatment efficacy, and service attitude. The total score was 100 points, with a score above 85 indicating satisfaction, a score between 60–85 denoting basic satisfaction, and a score below 60 indicating dissatisfaction.

Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics for Windows, Version 26.0. (IBM Corp., Armonk, NY, USA). For categorical variables, the χ^2 test or Fisher's exact test was employed. The independent sample T-test or Mann–Whitney U test was used for continuous variables. Subsequently, the propensity score matching (PSM) approach was employed for 1:1 matching. The matching variables included age, gender, diabetes history, hypertension history, location of TL, cause of TL, and the quantity of missing teeth. The nearest-neighbor matching algorithm was adopted during the matching process, with a matching ratio of 1:1. After matching, the balance of baseline data in both groups was re-evaluated. A caliper value of 0.02 was set. A P-value less than 0.05 was regarded as statistically significant.

Ethics: The Ethics Committee of Nanjing Stomatological Hospital approved the study (NJSH-2023NL-064).

RESULTS

Comparison of baseline data between observation group and control group before PSM

After screening based on the inclusion and exclusion criteria, 47 patients in the observation group and 73 patients in the control group were finally determined. As shown in Table 1, the two groups were not statistically different in sex and age ($p > 0.05$). However, the observation group had more patients with a smoking history and single-tooth loss than the control group, with higher treatment costs ($p < 0.05$). In addition, the number of people in the observation group whose place of residence was rural and whose educational level was junior high school or below was less than that in the control group, the age was younger, and the operation time was shorter ($p < 0.05$).

Evaluation of the balance of baseline variables in patients before and after PSM

We screened 47 patients in the observation group through PSM. As shown in Figure 2, the standardized mean differences (SMD) of multiple variables between the two groups were relatively high before matching, and significant differences were present in the distribution of propensity scores, indicating substantial differences in these variables between the two groups. After matching, the SMD of most variables approached 0, and the distribution conformed more closely to the normal distribution.

Comparison of baseline data between observation group and control group after PSM

We found no notable differences in age, sex, and number of missing teeth between the observation group and the control group after PSM ($p > 0.05$), suggesting significantly

improved comparability of baseline data between the two groups. Nevertheless, with respect to treatment costs, the observation group still exhibited higher values compared to the control group ($p < 0.05$, Table 2).

Comparison of plantation accuracy

After the follow-up, the implantation success rate of the observation group was 100% (47/47), versus 97.87% (46/47) of the control group, showing no statistical inter-group significance ($p < 0.05$). Although not reaching a statistically significant level, the 100% success rate in the observation group suggests that DIR-assisted implantation may have a clinical trend towards improved implantation success. The apical point error and implant angle error of patients in the observation group following implantation were both (0.57 ± 0.16) mm and (2.78 ± 0.34), which were lower than those in the control group ($p < 0.05$, Table 3).

Comparison of oral function

In terms of oral function, no significant differences were identified between the two groups with respect to language articulation and bite force ($p > 0.05$). However, the ratio of occlusal pressure to the contralateral homologous control tooth in the observation group was significantly higher than that in the control group ($p < 0.05$). Concerning pain assessment, no differences were observed in the VAS scores between groups at T0 and T3 ($p > 0.05$); Nevertheless, lower VAS scores were determined in the observation group versus the control group at T1 and T2 ($p < 0.05$, Table 4).

Comparison of treatment safety

Statistical analysis revealed that the incidence rate of postoperative complications in the observation group was 6.38%, with no infected cases. In contrast, the control group exhibited an incidence rate of 14.89%, with one infected patient. The comparison demonstrated no significant difference in the incidence rate of complications between the two groups ($p < 0.05$, Table 5).

Comparison of aesthetic effects and treatment satisfaction

Finally, in the comparison of post-implantation aesthetics, it was evident that both the PES and the WES were higher in the observation group than in the control group ($p < 0.05$). The results of the satisfaction survey indicated that there were no dissatisfied patients in either group. However, a greater number of satisfied patients was found in the observation group compared with the control group ($p < 0.05$, Table 6).

DISCUSSION

In this study, we reported the application effect of DIR through PSM. It was found that DIR significantly enhanced the accuracy of oral implant restoration and was more conducive to improving the occlusal function of patients. These findings provide a reliable data for future dental implant medicine.

Notably, the baseline data before PSM showed that the proportion of patients living in rural areas and the proportion of patients with education level of junior high school or below in the observation group were significantly lower than those in the control group. It is speculated that

this is because the place of residence and education level may indirectly affect the implant effect (such as complication rate, pain score VAS, aesthetic satisfaction) by affecting the patient's oral hygiene habits, compliance with postoperative doctor's advice, or perception and reporting of pain. However, the primary outcome measures (implant accuracy, bite force, and speech intelligibility) in this study were mainly affected by the surgical technique and the implant itself, and were relatively unlikely to be directly affected by the above socio-demographic factors, and we ensured comparability between the two groups by PSM. However, more attention should be paid to these potential confounding factors in the design and analysis of future studies. There was basically no difference in baseline data between the two groups after PSM, confirming that PSM can effectively control potential confounding variables and lay a more reliable foundation for the evaluation of the effect of DIR. The comparison results showed that the apical point error and implant angle error in the observation group were both lower than those in the control group, while the ratio of occlusal pressure to the contralateral homologous control tooth was higher. This is also in line with the research findings of Bahrami et al. [15], further validating the excellent application effect of DIR. As it is widely known, the traditional conventional dental implants primarily depend on dental implantologists' evaluations, which are based on preoperative CBCT results and the status of intra-oral dentition loss. In addition, the processes of cavity preparation and implant insertion during the surgical procedure rely on the surgeons' clinical expertise and tactile sense during implantation [16]. Research by Wang et al. [17] has pointed out that due to differences in the experience of dental implantologists, there may be deviations in the neck and angulation of the implant, or substantial deviations in the apical portion and depth of the implant during cavity preparation, affecting the path of insertion of the superstructure restoration. In contrast, the DIR manipulator can precisely operate by moving instruments in three-dimensional space, avoiding human errors caused by operational fatigue, suboptimal body positioning, or visual

blind spots, and reducing the complexity of the operation [18], thus further enhancing implantation accuracy. In terms of oral function recovery, there were no significant differences in speech clarity and bite force between the two groups. This is because the recovery of bite force depends mainly on the osseointegration quality of the implant, the design of the upper prosthesis, and the neuromuscular adaptation of the patient. In this study, both DIR-assisted and conventional implants followed standard osseointegration and repair procedures, which may be the main reason for the comparable bite force recovery between the two groups. The advantages of DIR in implant accuracy (such as more accurate insertion Angle and position) may be more reflected in the accuracy of prosthesis insertion and long-term stability, while the effect on maximum bite force at 1 year after surgery is limited. Additionally, Feng et al. [19] also mentioned that DIR guides the robotic arm through navigation to automatically complete the preparation of the implant cavity according to the preoperative plan. In the event of a slight displacement of the patient's head during the operation, the robotic arm can perform real-time updates and calibrations to ensure the precision and safety of the cavity preparation process. However, no significant difference was observed in the comparison of the incidence of complications between the two groups, which may be due to the accident caused by the small number of cases included in this study. Currently, the utilization of DIR has not achieved high prevalence, making it challenging for us to conduct a large-scale retrospective analysis. In the future, we will remain vigilant regarding this limitation.

On the other hand, the influence of TL extends beyond the pathological aspect and directly impacts the maxillofacial appearance of patients as well [20]. In traditional implant surgeries, the flap-elevation technique employed during the operation can prolong the surgical duration and cause pronounced postoperative pain. To a certain degree, this can impede the postoperative recovery of patients and lead to poor restoration outcomes. In this study, the PES and WES scores of patients in the observation group were both higher than those in the control

group, suggesting that DIR provides better results to improving the aesthetics of patients. Reasons for analysis: (i) The high-precision operation of DIR ensured that the implant was placed in the best three-dimensional position designed before the operation, and provided an ideal exit profile and support foundation for the prosthesis, which was conducive to the formation of a coordinated gingival margin curve, a full gingival papilla, and a natural crown shape. (ii) The precise navigation of DIR reduces the exploration and adjustment of soft and hard tissues during the operation. In general, the socket preparation and implantation can be completed without extensive flap surgery, and the original soft and hard tissue structure and blood supply in the planting area can be preserved to the maximum extent. Minimally invasive surgery can reduce tissue edema and scar formation after operation, and is conducive to the stability and recovery of soft tissue aesthetic morphology [7]. (iii) DIR can avoid implantation deviation caused by visual error or operator fatigue during free-hand operation, which may lead to poor contour of the crown or abnormal crown shape after insertion, which may affect the aesthetic effect. In a clinical application study of DIR, Wu et al. [21] also obtained the same results as this paper.

However, in this PSM study, it was observed that following the matching process, the treatment costs of the observation group remained significantly higher than those of the control group. This elevation in cost is associated with the utilization expense of the DIR and is, unfortunately, an unavoidable consequence. Although DIR has shown advantages in accuracy and aesthetic results, its high cost is an important challenge for clinical promotion. Future studies should conduct a more comprehensive cost-effectiveness analysis (CEA) that considers not only the initial Cost of treatment, but also the possible long-term benefits of DIR. The higher initial cost of DIR may be amortized if it significantly reduces the long-term complication rate or extends the lifespan of the prosthesis. Therefore, when evaluating the value of DIR, the cost and benefit need to be weighed from the perspective of the whole treatment cycle. Meanwhile, the

following issues cannot be overlooked: (i) Currently, DIR cannot completely perform the implantation surgery independently. Instead, it necessitates surgeons to engage in preoperative planning, surgical protocol design, and comprehensive intraoperative monitoring. Moreover, it cannot timely predict and make real-time adjustments for various unexpected situations during the operation. Therefore, in order to promote DIR technology, it is necessary to strengthen the professional and systematic training of dental implantologists, and develop more intelligent intraoperative monitoring and auxiliary decision-making systems to reduce the difficulty of operation and the absolute dependence on the experience of the doctor. (ii) DIR is generally bulky and needs sufficient operating space. (iii) Since DIR is a new technology, many patients find it difficult to accept it psychologically. In clinical practice, it is thus necessary to strengthen the education and publicity of DIR to enhance patients' awareness and acceptance.

Limitations

The number of cases in this study was small and we need to increase the number of cases to improve the representativeness and comprehensiveness of the results. In addition, there were fewer observational indicators in this study, and we should add more objective indicators (e.g., inflammatory factors, oxidative stress indicators, etc.) to observe the full impact of DIR. Finally, the follow-up time in the current study was short, which resulted in our inability to assess the impact of DIR on the long-term prognosis of TL. Therefore, we also need to conduct a longer follow-up investigation on the subjects of this study.

CONCLUSION

DIR effectively enhances the accuracy of oral implantation, reduce the apical error by about 13.6%, and ameliorates the aesthetic outcome for patients. This represents a high clinical value.

It is recommended that the use of DIR be promoted and popularized in clinical practice, thereby furnishing a more reliable treatment guarantee for dental implant medicine. The data emerging from this study are limited, and a larger prospective randomized clinical trial would be crucial to better study the application of this new technology.

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Conflicts of Interest: None declared.

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Table 1. Baseline information before propensity score matching

Variables		Control group (n = 73)	Observation group (n = 47)	t (or χ^2) values	p value
Age		48.90 ± 11.86	52.53 ± 9.69	1.753	0.082
Sex	male	49 (67.12)	30 (63.83)	0.138	0.710
	female	24 (32.88)	17 (36.17)		
Smoking history	yes	19 (26.03)	21 (44.68)	4.477	0.034
	no	54 (73.97)	26 (55.32)		
Drinking history	yes	21 (28.77)	18 (38.30)	1.184	0.277
	no	18 (38.30)	29 (61.70)		
Education level	Junior high school and below	29 (39.73)	10 (21.28)	4.436	0.035
	High school and above	44 (60.27)	37 (78.72)		
Place of residence	urban	36 (49.32)	34 (72.34)	6.237	0.013
	rural	37 (50.68)	13 (27.66)		
Number of tooth loss	single	31 (42.47)	29 (61.70)	4.232	0.040
	double and	42 (57.53)	18 (38.30)		
Location of tooth loss	premolars	18 (24.66)	9 (19.15)	0.498	0.481
	molar	55 (75.34)	38 (80.85)		
Reason for tooth loss	periodontics	34 (46.58)	26 (55.32)	0.898	0.638
	dental caries	29 (39.73)	16 (34.04)		
	trauma	10 (13.70)	5 (10.64)		
Operation time (min)		34.77 ± 10.92	27.51 ± 6.05	4.158	< 0.001
Treatment costs (yuan)		5008.84 ± 784.54	8438.57 ± 598.93	25.550	< 0.001

Table 2. Baseline information after propensity score matching

Variables		Control group (n = 47)	Observation group (n = 47)	t (or χ^2) values	p value
Age		49.04 ± 12.48	52.53 ± 9.69	1.514	0.133
Sex	male	27 (57.45)	30 (63.83)	0.401	0.527
	female	20 (42.55)	17 (36.17)		
Smoking history	yes	17 (36.17)	21 (44.68)	0.707	0.401
	no	30 (63.83)	26 (55.32)		
Drinking history	yes	14 (29.79)	18 (38.30)	0.758	0.384
	no	33 (70.21)	29 (61.70)		
Education level	junior high school and below	17 (36.17)	10 (21.28)	2.546	0.111
	high school and above	30 (63.83)	37 (78.72)		
Place of residence	urban	28 (59.57)	34 (72.34)	1.706	0.192
	rural	19 (40.43)	13 (27.66)		
Number of tooth loss	single	26 (55.32)	29 (61.70)	0.394	0.530
	double and	21 (44.68)	18 (38.30)		
Location of tooth loss	premolars	10 (21.28)	9 (19.15)	0.066	0.797
	molar	37 (78.72)	38 (80.85)		
Reason for tooth loss	periodontics	22 (46.81)	26 (55.32)	1.056	0.590
	dental caries	17 (36.17)	16 (34.04)		
	trauma	8 (17.02)	5 (10.64)		
Operation time (min)		30.21 ± 9.11	27.51 ± 6.05	1.694	0.094
Treatment costs (yuan)		5036.40 ± 856.23	8438.57 ± 598.93	22.320	< 0.001

Table 3. Plantation accuracy of the two groups of patients

Variables	Control group (n = 47)	Observation group (n = 47)	t (or χ^2) values	p value
Implantation success rate	46 (97.87)	47 (100%)	1.011	0.315
Apical point error (mm)	0.66 ± 0.23	0.57 ± 0.16	2.298	0.024
Implant angle error (°)	3.24 ± 1.07	2.78 ± 0.34	2.818	0.006

Table 4. Oral function of the two groups of patients

Variables		Control group (n = 47)	Observation group (n = 47)	t value	p value
Oral function	Respect to language articulation (%)	89.92 ± 2.65	90.40 ± 2.19	0.963	0.338
	Bite force (N)	20.06 ± 2.84	20.96 ± 3.84	1.291	0.200
	Ratio of occlusal pressure to the contralateral homologous	0.79 ± 0.13	0.92 ± 0.17	4.303	< 0.001
Visual analogue scale	T0	5.38 ± 1.01	5.28 ± 1.06	0.498	0.619
	T1	3.49 ± 1.00	2.72 ± 0.80	4.108	< 0.001
	T2	2.30 ± 0.88	1.87 ± 0.99	2.198	0.031
	T3	0.72 ± 0.45	0.60 ± 0.50	1.304	0.196

Table 5. Treatment safety of the two groups of patients

Groups	Loose implants	Inflammation of the gums	Infection	Severe pain	Tearing of the wound	Incidence rate
Control group (n = 47)	1 (2.13)	2 (4.26)	1 (2.13)	2 (4.26)	1 (2.13)	14.89
Observation group (n = 47)	0 (0)	1 (2.13)	0 (0)	2 (4.26)	1 (2.13)	6.38
χ^2 values						1.790
p value						0.181

Table 6. Aesthetic effects and treatment satisfaction of the two groups of patients

Parameters		Control group (n = 47)	Observation group (n = 47)	t value	p value
Aesthetic effects	Pink Esthetic Score	9.32 ± 1.07	10.60 ± 10.35	5.099	< 0.001
	White Esthetic Score	8.89 ± 1.03	9.79 ± 1.88	2.865	0.005
Satisfaction	Satisfaction	29 (61.70)	38 (80.85)	4.209	0.040
	Basic satisfaction	18 (38.30)	9 (19.15)		
	Dissatisfied	0 (0)	0 (0)	-	-

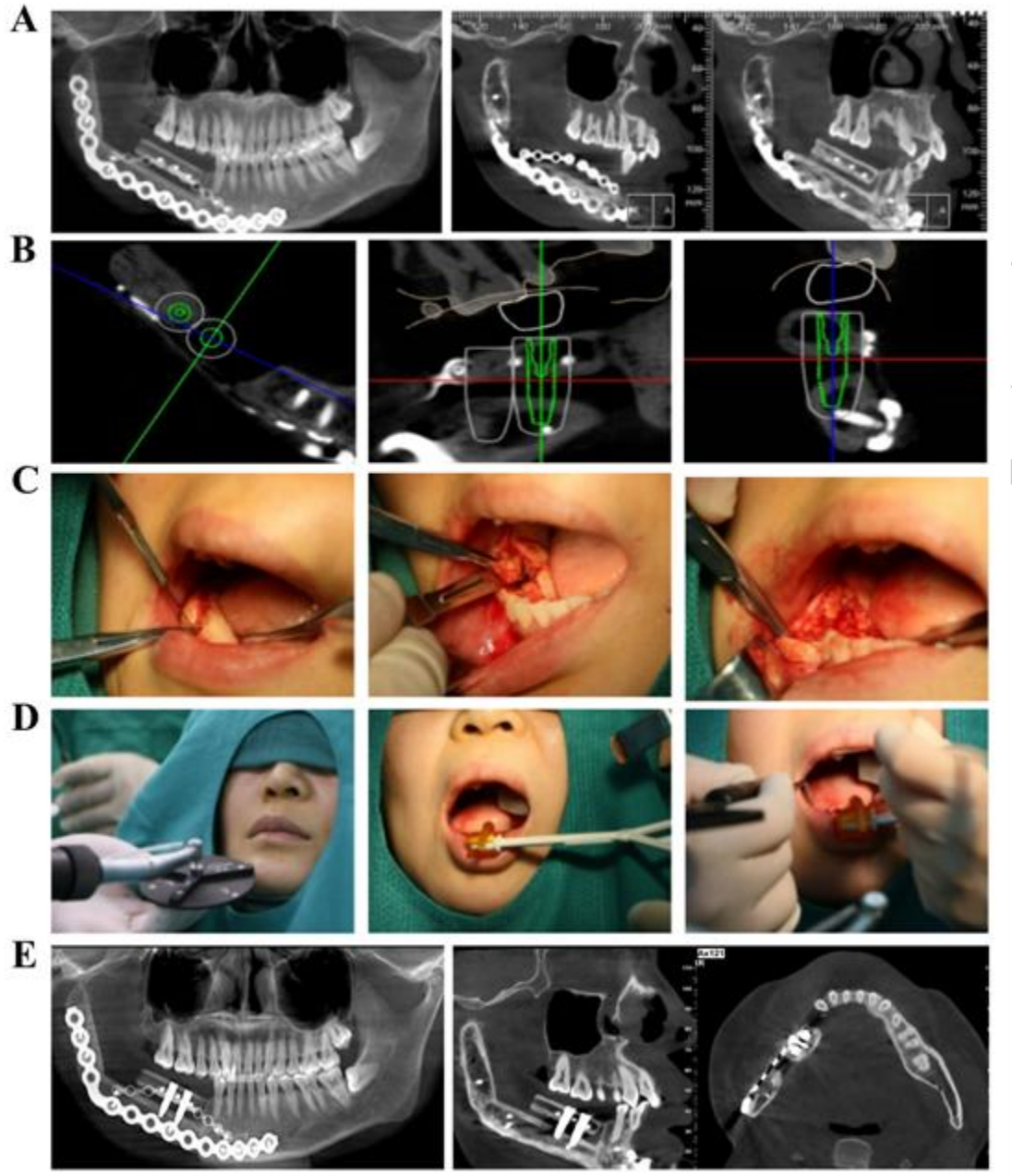

Figure 1. Schematic diagram of the surgical procedure; A – cone-beam computed tomography taken before surgery; B – design of implant position and implant path; C, D – the process of surgical operation; E – review of cone-beam computed tomography after surgery

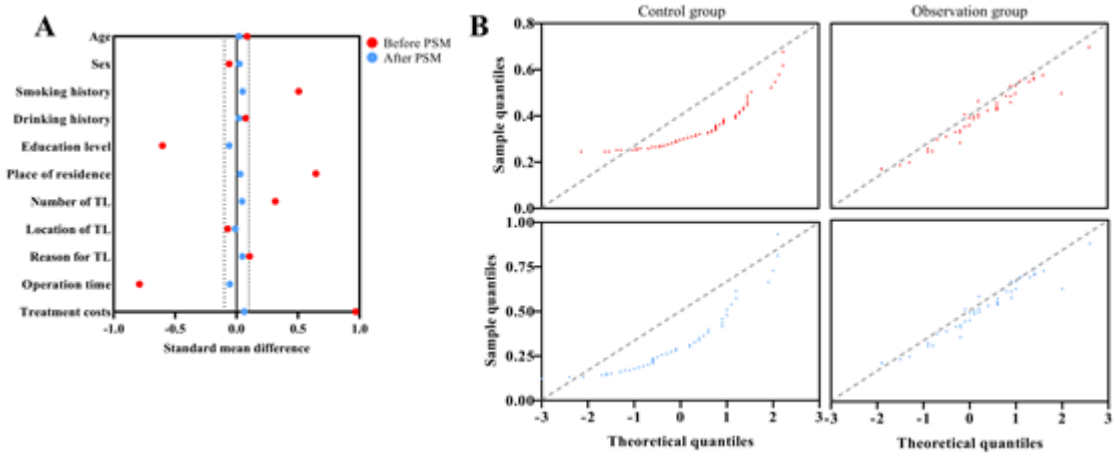

Figure 2. Effectiveness check of propensity score matching (PSM); A – standardized mean differences changes in variables before and after PSM; B – distribution of variables before and after PSM; TL – tooth loss

