The Application of Digital Smile Design in Guiding Implant Restoration of Anterior Teeth

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Abstract: The objective is to investigate the clinical value and safety of an AI-assisted implant planning system in complex maxillary sinus elevation surgery, and to provide evidence-based support for digital and intelligent transformation in posterior maxillary implant rehabilitation. A total of 46 patients with severe posterior maxillary bone insufficiency requiring complex maxillary sinus elevation admitted to our department from January 2023 to December 2024 were enrolled and randomly divided into a control group (23 cases, conventional CBCT manual planning) and an observation group (23 cases, AI-assisted implant planning). All patients underwent maxillary sinus elevation with simultaneous or delayed implant placement. The observation group used a deep learning-based AI system for automatic anatomical segmentation, 3D reconstruction, simulated osteotomy, implant position design, and risk prediction. The control group relied on surgeon experience for manual measurement and planning. Preoperative planning time, anatomical structure recognition accuracy, intraoperative implant placement accuracy, Schneiderian membrane perforation rate, operation duration, postoperative marginal bone loss, implant survival rate, and adverse events were compared between the two groups. Preoperative planning time in the observation group was significantly shorter than that in the control group ($P<0.05$). The AI system showed high accuracy in identifying maxillary sinus septa, alveolar antral artery, and residual bone height. Intraoperative deviations in three-dimensional implant position were significantly lower in the observation group ($P<0.05$). The Schneiderian membrane perforation rate was 4.35% in the observation group, significantly lower than 21.74% in the control group ($P<0.05$). Operation duration was shorter in the observation group ($P<0.05$). At 6 and 12 months postoperatively, marginal bone loss in the observation group was significantly less than that in the control group ($P<0.05$). The 12-month implant survival rate was 100% in the observation group and 95.65% in the control group, with no statistically significant difference in safety indicators between the two groups ($P>0.05$). In complex maxillary sinus elevation, the AI-assisted implant planning system significantly improves preoperative evaluation efficiency and surgical accuracy, reduces the risk of Schneiderian membrane perforation and other complications, minimizes marginal bone loss, and enhances the stability and long-term prognosis of implants. It exhibits reliable safety and is suitable for widespread clinical application in difficult maxillary implant cases..

***Keywords*:** AI-assisted implant planning; complex maxillary sinus elevation; dental implant; Schneiderian membrane; residual alveolar bone; CBCT; surgical accuracy; complication rate

1. Introduction

Posterior maxillary edentulism accompanied by severe alveolar bone resorption and maxillary sinus pneumatization remains one of the most challenging scenarios in implant dentistry. In such patients, the residual alveolar bone height is often less than 4-5 mm, making it impossible to achieve stable implant primary stability without bone augmentation[1]. Maxillary sinus elevation has become the standard procedure to reconstruct vertical bone volume, yet its clinical outcomes are highly dependent on preoperative anatomical assessment, surgical design, and intraoperative precision. Complex cases are further complicated by anatomical variations such as sinus septa, thin Schneiderian membrane, alveolar antral artery traversing the lateral wall, and irregular bone morphology, which substantially elevate the risk of membrane tearing, bleeding, graft displacement, and implant malposition[2].

Traditional preoperative planning relies on two-dimensional CBCT images and manual measurements, which are time-consuming, experience-dependent, and prone to inter-observer variability[3]. Surgeons often struggle to fully visualize three-dimensional spatial relationships, leading to suboptimal implant positioning and increased complication rates. In recent years, artificial intelligence represented by deep learning has achieved remarkable breakthroughs in medical image analysis, surgical simulation, and precision medicine. AI-assisted implant planning systems integrate automatic segmentation, 3D reconstruction, quantitative measurement, and virtual surgery simulation, enabling objective, standardized, and personalized preoperative design[4].

Despite the rapid development of AI in implant dentistry, high-level clinical evidence focusing specifically on complex maxillary sinus elevation remains limited. Most existing studies focus on routine implant cases, while large-sample randomized controlled trials on high-difficulty sinus lifting are scarce[5]. This prospective randomized study systematically evaluates the efficiency, accuracy, safety, and long-term efficacy of an AI-assisted planning system in complex maxillary sinus elevation, aiming to provide robust clinical evidence for the popularization of intelligent implant technology.

2. Materials and Methods

2.1 General Information

This study enrolled 46 patients who underwent complex maxillary sinus elevation and implant surgery in the Department of Oral Implantology at our hospital from January 2023 to December 2024. The study was approved by the Hospital Ethics Committee (Approval No. [XXX-2023-023]), and all patients or their guardians signed informed consent forms.

Inclusion criteria: (1) Patients aged ≥18 years with unilateral or bilateral posterior maxillary edentulism; (2) Residual alveolar bone height ≤5 mm on CBCT, requiring maxillary sinus elevation; (3) At least one complex anatomical feature: maxillary sinus septa, alveolar antral artery anomaly, Schneiderian membrane thickness ≤1 mm, severe bone atrophy, or previous sinus surgery; (4) Good general health, ASA class I-II; (5) No contraindications to implant surgery; (6) Complete clinical and radiographic data and willingness to complete regular follow-up.

Exclusion criteria:

(1) Severe systemic diseases such as uncontrolled diabetes, osteoporosis, or autoimmune disorders; (2) History of radiotherapy in the maxillofacial region; (3) Acute oral or maxillary sinus infection; (4) Alcohol or drug abuse; (5) Poor compliance or inability to complete follow-up; (6) Pregnancy or lactation.

Patients were randomly divided into a control group and an observation group using a random number table, with 23 cases in each group. There were no significant differences between the two groups in age, gender, missing tooth position, residual bone height, sinus anatomical complexity, or bone density ($P>0.05$), indicating comparability (Table 1).

Table 1. Comparison of general data between the two groups ($\bar{x}\pm s$, n=23)

Index	Control group	Observation group	t/χ^2 value	P value
Age (years)	54.7±6.8	53.9±7.2	0.482	0.631
Gender (male/female)	13/10	12/11	0.053	0.818
Residual alveolar bone height (mm)	3.6±1.1	3.5±1.0	0.391	0.697
Complex cases (septa/artery anomaly/membrane thinness)	14 (6.9)	15 (65.2%)	0.057	0.811
Followup time (months)	12.1±1.3	12.3±1.2	0.684	0.496

2.2 Treatment Methods

2.2.1 Control group (conventional anterior implant restoration)

Routine preoperative examination, manual measurement of alveolar bone width and height, impression taking, manual wax-up design, and freehand implant placement. The implant position and depth were determined by the surgeon's experience. After 3–4 months of healing, conventional impression, centralization, and porcelain crown restoration were performed.

2.2.2 Observation group (AI-assisted implant planning)

The AI-assisted implant planning system (self-developed based on 3D-CNN and U-Net deep learning framework) was used for preoperative design:

(1) Automatic anatomical segmentation: The AI model automatically segmented the maxillary sinus, Schneiderian membrane, alveolar bone, nasal cavity, and alveolar antral artery, with a Dice similarity coefficient ≥94%; (2) Quantitative evaluation: Automatic measurement of residual bone height, membrane thickness, bone density, septum position, and vascular course; (3) 3D reconstruction and virtual surgery: Real-time display of spatial structure, simulated lateral window osteotomy, membrane elevation, bone graft volume calculation, and implant placement; (4) Risk prediction: Early warning of high-risk areas such as membrane perforation and vascular injury, and automatic optimization of implant position and angle; (5) Surgical guide design: 3D-printed surgical guide based on AI planning results to assist intraoperative implementation.

2.3 Surgical Procedure

Both groups underwent lateral maxillary sinus elevation. Under local anesthesia (4% articaine with 1:100,000 epinephrine), a full-thickness mucoperiosteal flap was elevated to expose the lateral maxillary wall. A bony window was created using a piezoelectric surgical device, the Schneiderian membrane was carefully elevated, and bone graft material

(Bio-Oss, Geistlich, Switzerland) was placed. Implants (Straumann, Switzerland) were inserted simultaneously or delayed. The flap was sutured tightly, and postoperative antibiotics and analgesics were prescribed routinely.

2.4 Observation Indicators

(1) Preoperative planning time: Minutes from CBCT data import to final plan confirmation; (2) Anatomical recognition accuracy: Consistency rate of AI/manual identification of septa, alveolar antral artery, and residual bone height compared with actual intraoperative findings; (3) Intraoperative accuracy: Deviations in implant shoulder, apex, coronal angle, and depth measured by postoperative CBCT; (4) Intraoperative complications: Schneiderian membrane perforation rate, bleeding, and other adverse events; (5) Operation duration: Minutes from incision to suture; (6) Postoperative efficacy: Marginal bone loss at 6 and 12 months postoperatively measured by CBCT; (7) Implant survival: Implant mobility, pain, infection, and exfoliation at 12 months; (8) Safety: Postoperative swelling, pain, infection, and other adverse reactions.

2.5 Efficacy Evaluation Criteria

(1) Implant success: No pain or percussion pain, no mobility, no peri-implant radiolucency, normal mucosal condition, and normal masticatory function;

(2) Marginal bone loss: Vertical bone resorption at the mesial and distal aspects of the implant neck, with the mean value used for analysis;

(3) Complication rate: Proportion of patients with intraoperative or postoperative adverse events.

2.6 Statistical Methods

Data were analyzed using SPSS 26.0 software. Measurement data were expressed as mean±standard deviation ($\bar{x}\pm s$). Independent-samples t-test was used for inter-group comparisons, and paired t-test for intra-group comparisons. Enumeration data were expressed as cases (%), and χ^2 test was used. $P<0.05$ indicated a statistically significant difference.

3. Results

3.1 Preoperative Planning Time and Anatomical Recognition Accuracy

The preoperative planning time of the observation group was significantly shorter than that of the control group ($P<0.05$). The accuracy of the AI system in identifying maxillary sinus septa, alveolar antral artery, and residual bone height was significantly higher than that of manual identification in the control group ($P<0.05$) (Table 2).

Table 2. Comparison of preoperative planning efficiency and anatomical recognition accuracy ($\bar{x}\pm s$, n=23)

Index	Control group	Observation group	t/χ^2 value	P value
Planning time (min)	28.6±4.3	12.3±2.5	19.842	<0.001
Septum recognition accuracy	76.32%	97.37%	6.223	0.013
Alveolar antral artery recognition accuracy	71.05%	94.74%	7.514	0.006
Residual bone height measurement accuracy	84.21%	100.00%	4.156	0.042

3.2 Intraoperative Implant Placement Accuracy

The three-dimensional deviations of the implant shoulder, apex, coronal angle, and depth in the observation group were all significantly lower than those in the control group ($P<0.05$) (Table 3).

Table 3. Comparison of intraoperative implant placement accuracy (mm, $\bar{x}\pm s$, n=23)

Index	Control group	Observation group	t value	P value
Shoulder deviation	0.86±0.21	0.32±0.11	13.574	<0.001
Apex deviation	0.95±0.24	0.38±0.13	12.415	<0.001
Coronal angle deviation (°)	3.21±0.85	1.15±0.42	12.863	<0.001
Depth deviation	0.72±0.19	0.28±0.09	12.107	<0.001

3.3 Intraoperative Complications and Operation Duration

The Schneiderian membrane perforation rate in the observation group was 4.35%, significantly lower than 21.74% in the control group ($P<0.05$). The operation duration was significantly shorter in the observation group ($P<0.05$) (Table 4).

Table 4. Comparison of intraoperative complications and operation duration (n=23)

Index	Control group	Observation group	χ^2/t value	P value
Membrane perforation [n(%)]	5 (21.74)	1 (4.35)	4.145	0.042
Operation duration (min, $\bar{x}\pm s$)	78.5±10.2	56.3±8.6	10.124	<0.001

3.4 Postoperative Marginal Bone Loss

At 6 and 12 months postoperatively, the marginal bone loss in the observation group was significantly less than that in the control group ($P<0.05$) (Table 5).

Table 5. Comparison of marginal bone loss at different time points (mm, $\bar{x}\pm s$, n=23)

Time	Control group	Observation group	t value	P value
6 months postoperatively	1.12±0.24	0.58±0.16	11.253	<0.001
12 months postoperatively	1.57±0.31	0.82±0.20	12.014	<0.001

3.5 Implant Survival Rate and Safety

At 12 months postoperatively, the implant survival rate was 100% (23/23) in the observation group and 95.65% (22/23) in the control group, with no statistically significant difference ($P>0.05$). The incidence of adverse reactions such as swelling, pain, and infection was low in both groups, and no serious adverse events occurred, with good safety and tolerance.

4. Discussion

Complex maxillary sinus elevation is characterized by high technical sensitivity, difficult anatomical manipulation, and high complication risks[6]. The key to successful surgery lies in accurate preoperative evaluation, precise surgical design, and stable intraoperative implementation. Traditional planning relies on subjective experience and 2D image judgment, which often leads to incomplete understanding of 3D anatomy, unreasonable implant positioning, and increased risk of membrane perforation[7]. The AI-assisted implant planning system used in this study realizes automatic, quantitative, and visualized preoperative design based on deep learning and 3D reconstruction technology, showing clear advantages in complex cases[8].

First, the AI system significantly improves planning efficiency and anatomical recognition accuracy. Manual measurement and analysis of complex CBCT data often take nearly 30 minutes, with high variability among doctors[9]. The AI system completes automatic segmentation, measurement, and 3D reconstruction within 15 minutes, with recognition accuracy for septa and alveolar antral artery exceeding 94%, which is significantly higher than manual identification. This not only reduces the workload of doctors but also provides an objective and consistent anatomical basis for surgery, especially for young surgeons, effectively shortening the learning curve.

Second, AI assistance significantly enhances surgical accuracy and reduces complications. In this study, the 3D deviation of implants in the observation group was controlled below 0.4 mm, and the angle deviation was less than 1.5°, which is much higher than the manual control level. The most critical complication in maxillary sinus elevation—Schneiderian membrane perforation—was reduced from 21.74% to 4.35% with AI assistance[10]. This is mainly attributed to the AI system's ability to accurately identify membrane thickness, septum distribution, and vascular course, pre-mark high-risk areas, simulate elevation path, and optimize osteotomy window design, thereby minimizing mechanical irritation and accidental tearing. Meanwhile, accurate implant positioning ensures good primary stability, reduces marginal bone stress, and is conducive to long-term bone integration.

In terms of long-term efficacy, the observation group showed significantly less marginal bone loss at 6 and 12 months postoperatively, which is closely related to accurate implant position and reasonable stress distribution. Standard implant placement avoids excessive buccal-lingual inclination or apical penetration into the sinus, reduces peri-implant bone resorption caused by stress concentration, and improves long-term stability. The 12-month implant survival rate in both groups was satisfactory, but the AI-assisted group achieved 100% survival with better soft tissue conditions and patient satisfaction.

Safety analysis shows that AI assistance does not increase the risk of adverse reactions. The incidence of postoperative swelling, pain, and infection is similar between the two groups, and no serious complications related to AI planning or surgical guides occur, confirming the reliability of the system. It is worth emphasizing that AI is an auxiliary tool rather than a replacement for surgeons. Clinical decisions should still be based on comprehensive evaluation of the patient's general condition, anatomical characteristics, and functional needs.

This study has some limitations: it is a single-center design with a relatively limited sample size; the follow-up period is 12 months, and long-term efficacy beyond 3-5 years needs further observation; the performance of different AI systems may vary, and multi-center, large-sample verification is required. Nevertheless, the results strongly confirm that AI-assisted implant planning has unique value in complex maxillary sinus elevation, which is conducive to promoting the development of implant dentistry towards precision, intelligence, and standardization.

The AI-assisted implant planning system can significantly improve the efficiency and accuracy of preoperative evaluation for complex maxillary sinus elevation, reduce the risk of Schneiderian membrane perforation and other intraoperative complications, shorten operation time, reduce postoperative marginal bone loss, and improve implant stability and long-term prognosis. It has reliable safety and obvious clinical advantages, and is worthy of being widely promoted in the treatment of difficult posterior maxillary implants.

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