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A longitudinal digital workflow enables the digital PBL-CBL method in teaching Lateral Window Sinus Augmentation

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Abstract

Background.

The PBL-CBL method reliant on 2-D imaging and limited clinical observation cannot effectively develop competencies for high-stakes procedures. The digital PBL-CBL method with a full digital workflow can intuitively visualize the intricate anatomical structures, detailed surgical planning and execution. This study aimed to establish a longitudinal digital workflow of lateral window sinus augmentation (LWSA) and evaluate the effect of digital PBL-CBL method using the digital workflow on teaching LWSA.

Materials & Methods.

A longitudinal digital workflow was constructed for LWSA, integrating virtual anatomical demonstration via 3-D reconstruction, virtual surgical planning based on CBCT and optical scan data, dynamic intraoperative video via an endoscope, microCT and histological data, and follow-up records. Fifty-seven postgraduate students were randomly allocated to three groups: the traditional PBL-CBL group (trained with the PBL-CBL method), the digital PBL-CBL group (trained with the digital PBL-CBL method), and a didactic teacher-centered control group. Following a three-month training, students' perceptions regarding the teaching methods were gathered via a feedback questionnaire. A theory test and a case analysis were respectively used to evaluate students’ mastery of knowledge and problem-solving abilities.

Results.

Thirty LWSA cases were integrated into the clinical digital workflow. With assistance of the digital workflow, the digital PBL-CBL method achieved significantly higher rate of satisfaction than the traditional PBL-CBL and teacher-centered methods in all items, except for “This approach decreases extracurricular work”. Furthermore, both the case analysis and theory test scores of the digital PBL-CBL group were significantly higher than the other two groups. The digital PBL-CBL teaching method significantly enhanced the students’ mastery of theoretical knowledge, practical thinking and clinical problem-solving abilities.

Conclusion.

The digital PBL-CBL teaching method, supported by a longitudinal digital workflow of LWSA, was proved highly effective in teaching this complex surgical procedure. This "data-driven" and immersive teaching method establishes a promising alternative for standardizing, securing, and enhancing skill acquisition in complex oral surgery training.

Trial Registration:

This trial was registered at the Chinese Clinical Trial Registry with registration number (ChiCTR2300068017) on February 03, 2023 (Retrospectively registered).

Introduction

The severely atrophic posterior maxilla presents a significant challenge for placing dental implants [1]. Lateral window sinus augmentation (LWSA) is a surgical technique specifically designed to address this clinical dilemma by elevating the Schneider membrane through a window on the side wall and filling in large amounts of grafting materials [2, 3]. Compared with other procedures in implant dentistry, LWSA is generally regarded as more technically demanding and associated with higher inherent risk [4]. The elevation of the extremely delicate sinus membrane is performed semi-blindly, resulted in a high risk rate of perforation ranging from 10% to 60% in different studies [5, 6]. Anatomical factors including a minimal residual bone height, a concave or septated sinus floor, a thin sinus membrane, or aberrant vascular canals can instantly escalate the complexity from moderate to high [7]. Besides, the surgical site neighbors the orbit, the nasal cavity, and the posterior superior alveolar artery, violation of which may lead to significant hemorrhage, orbital complications, or oroantral communications [8]. Therefore, standardized and efficient teaching of LWSA is essential for students or trainees in oral and maxillofacial education to minimize complications and enhance success rates.

The inherent technical complexities of LWSA procedure also pose significant challenges to teaching of LWSA. LWSA is performed through a small bony window in the posterior maxilla, providing extremely limited access [9]. Instructors are unable to directly "show" the exact technique whether in reality or in video. Students must mentally translate CBCT scans into a three-dimensional surgical pathway and dynamic instrument navigation, which requires good 3D spatial reasoning. In addition, maxillary sinus varies a great deal regarding the topography of sinus floor, the thickness of the Schneiderian membrane, the condition of intra-sinus septa, the distribution of neurovascular canals and the occasional presence of mucosal cysts [10–13]. The teachers must focus on developing the trainee's ability to formulate a personalized surgical plan for each patient. Furthermore, challenges in teaching LWSA also lies in the difficulty in displaying the intra-sinus grafted bone to students. CBCT imaging can only display the volume and contour of the augmented area, but not the texture of newly formed bone [14], making it difficult to explain the causes of implant failure following the seemingly successful LWSA confirmed by CBCT.

Considering these challenges, the pedagogical approach for LWSA should specifically facilitate 3D spatial reasoning, flexible decision-making, and causal analysis. Problem-Based Learning (PBL) and Case-Based Learning (CBL) are two major approaches predicated on active engagement with realistic clinical problems [15, 16]. Our previous research proved that an integrated PBL-CBL approach combines the advantages of PBL and CBL, and yields superior outcomes compared to the traditional method [17]. However, teaching reliant on two-dimensional imaging and limited clinical observation often fail in

cultivating the integrated cognitive and psychomotor competencies essential for performing high-stakes procedures [18, 19]. We then introduced c into PBL-CBL teaching of the bone grafting technique in anterior maxilla, named as digital PBL-CBL, which was proved to work better than the conventional PBL-CBL [20]. Within the digital world, students can intuitively visualize the intricate anatomical structures as well as detailed surgical planning and execution [21], suggesting digital PBL-CBL may serve as a potential solution to the pedagogical challenges associated with LWSA.

The efficacy of any digital curriculum is fundamentally constrained by the quality, richness, and structure of its underlying clinical data [22]. Different from the anterior maxilla, where collection of digital clinical data is highly feasible, digital PBL-CBL for LWSA faces a pronounced lack of organized digital clinical data that encompasses the full clinical continuum. This study is designed to: (1) establish a longitudinal digital workflow of LWSA clinical data, including virtual anatomical demonstration based on CBCT data and digital photograph at all time-points, virtual surgical planning based on CBCT and optical scan data, dynamic intraoperative microscope video, biological data (microCT and histological sections), and postoperative follow-up records; (2) leverage these data to develop a new digital PBL-CBL curriculum and preliminary evaluate its effects on LWSA teaching.

Materials and methods

Students and grouping

This study received approval from the Ethics Committee of the Affiliated Stomatological Hospital of Chongqing Medical University (Approval No. xyjg220209) and was conducted in compliance with the ethical principles of the Declaration of Helsinki. All students provided written informed consent. Fifty-seven postgraduate students trained in the Department of Implant Dentistry at the Affiliated Stomatological Hospital of Chongqing Medical University between 2023 and 2025 were included. None of the participants had prior experience or training in LWSA. Students were randomly allocated to three groups: the traditional PBL-CBL group (trained with the PBL-CBL method), the digital PBL-CBL group (trained with the digitally supported PBL-CBL method), and a didactic teacher-centered control group. All groups were trained for three months.

Clinical workflow of LWSA digital cases

Patients with posterior maxillary tooth loss at the Department of Dental Implantology were included in the longitudinal digital workflow if their preoperative CBCT scans demonstrated a sinus-crest distance of less than 3 mm. The patients expressed a strong preference for implant-supported restorations and rejected fixed or removable prostheses. The clinician determined that transcrestal sinus elevation was not feasible, leaving LWSA and staged implant placement as the only viable surgical approach. Four major steps were taken to collect digital LWSA cases (Fig. 1):

Step 1. Digital diagnosis and virtual LWSA plan (Fig. 2). Acquire the patient's intraoral scan (3Shape, Copenhagen, Denmark) (Fig. 2A), virtual teeth arrangement (Fig. 2B) and CBCT data (Kava, Biberach, Germany) (Timepoint 0, T0) (Fig. 2C). Design the three-dimensional implant position based on the ideal prosthesis position (Fig. 2D). Using the virtual implant position as the baseline, precisely measure the parameters at the implant site, including sinus-crest distance, depth of implant penetration into the maxillary sinus, cortical integrity of the sinus floor, and specific anatomical structures within the maxillary sinus, such as blood vessels, septa, and cyst (Fig. 2D). The cyst could be intuitively visualized in terms of its location, size, morphology, and internal density using 3DSlicer 4.10.2 software (The Brigham and Womens Hospital, Inc. Boston, MA, USA), thereby assisting clinicians in determining whether cyst excision or localized elevation was the more appropriate treatment approach (Fig. 2E). The three-dimensional anatomical structures were segmented and reconstructed through the surgical navigation software (RemebotDent, Beijing China), enabling independent visualization of the morphology and location of the anterior, medial, posterior, and lateral walls of the maxillary sinus (Fig. 2F). According to the position of dental implants, determine the volume and distribution of bone substitutes virtually (Fig. 2G). Design the location and size of the lateral window for sinus augmentation. Print a surgical guide based on the virtual lateral window (Fig. 2H).

Step 2. Perform LWSA and acquire CBCT data of the augmented bone (Fig. 3). Prepared a trapezoidal mucosal flap (Fig. 3A) and a bony window on the lateral wall of the maxillary sinus under the guidance of the LWSA guide (Fig. 3B). Elevated the sinus membrane using a DASK kit and examed the condition of sinus membrane using a sinus endoscope (Fig. 3C). Placed concentrated growth factors (CGF) (Figs. 3D and 3E) and sticky bone in the created space using the predetermined amount of deproteinized bovine bone mineral (Figs. 3F and 3G). Closed the wound without tension (Fig. 3H). Perform CBCT scanning immediately after LWSA (T1).

Step 3. Perform staged implant placement and acquire imaging, microCT and histological data of the augmented bone in sinus (Fig. 4). Perform CBCT scanning 9 to 12 months after LWSA (before implantation, T2). Following flap elevation (Fig. 4A) and preparation of implant osteotomies (Fig. 4B), the implants were placed at the preoperatively planned positions (Fig. 4C). A trephine drill with an internal diameter of 3.0 mm and a cutting length of 10.0 mm was used to collect a core bone biopsy at the site of implant under the guidance of implant surgical guide (Figs. 4D and 4E), which was used for microCT scanning (Fig. 4F) and histological analysis (Figs. 4G and 4H). Implants were screwed in and submerged before the uncover surgery. Perform CBCT scanning immediately after implant placement (T3).

Step 4. Perform uncover surgery, final restoration and acquire imaging data of the augmented bone. Perform CBCT scanning 6 months after implant placement (T4). Uncover the implant and make optical impression. The final restoration was seated.

Integration of digital data

The CBCT, micro-CT and histological data were integrated for each case to digitally reveal volumetric, micro-structural and histological changes of the augmented bone (Fig. 5). The 3D jawbone model was established by CBCT dicom data taken preoperatively (T0), immediately after LWSA (T1), before implantation (T2), and 6 months after implant placement (T4) using Mimics Research 21.0 (Materialise, Leuven, Belgium) (Figs. 5A and 5B). The augmented bone at different time points were calculated by superimposing the jawbone model reconstructed at T0 and other time point after LWSA (Fig. 5B). The contour of augmented bone at T1, T2 and T4 were superimposed to show changes in volume and shape (Fig. 5C). The 3D jawbone models reconstructed at different time points were automatically aligned with the model at T0 respectively via a registration tool in 3DSlicer 4.10.2 software (The Brigham and Womens Hospital, Inc. Boston, MA, USA) (Fig. 5D). Changes in mineral density were showed by density contour map (Fig. 5D). To annotate corresponding microCT structures and histological data on the CBCT-reconstructed model at T2, the jawbone model reconstructed at T2 and T3 was superimposed on each other using 3DSlicer 4.10.2 software (The Brigham and Womens Hospital, Inc. Boston, MA, USA) to show the correct location of the biopsy from where it was harvested (Fig. 5E).

Teaching methods

All students completed a structured curriculum comprising six modules on LWSA, covering the following topics “1. Anatomy of maxillary sinus”, “2. definition and indication for LWSA”, “3. Pre-surgical CBCT assessments and treatment plan”, “4. Surgical Techniques of LWSA”, “5. Assessment of bone augmentation results”, and “6. Management of Complications”. The curriculum was delivered over four sessions, each lasting eighty minutes. In the control group, courses were delivered using a conventional teacher-centered lecture format, without scheduled structured discussion during or after the sessions. In contrast, students in the traditional and digital PBL-CBL groups engaged in collaborative learning within small teams of three or four members at each of sessions. Teachers shifted their role from traditional knowledge-authorities to primarily narrating cases and facilitating discussion. PBL and CBL were integrated following our previous studies [17, 20]. The clinical scenarios presented to the two PBL-CBL groups were the same, including past medical history, clinical manifestations, radiographic findings, diagnosis, and treatment processes. The two groups differed mainly in case presentation: traditional PBL-CBL used text and images, while digital PBL-CBL employed a digital workflow with virtual animations, data analysis, and objective evaluation. All groups covered the same content with equal emphasis, and had identical total duration and sessions.

Evaluation methodology

Teaching effectiveness was assessed across the following three aspects. Exams were graded by two teachers in implant department blinded to student identities and group assignments.

1. Anonymous questionnaire

Subjective student feedback regarding the different teaching methods was collected through an anonymous post-training questionnaire, which was composed of eight questions. The items were listed in Table 1.

Table 1
Rate of satisfaction with the three teaching methods.

Items surveyed	Rate of satisfaction			P value
	Digital PBL-CBL	Traditional PBL-CBL	Control	
1. I like this approach	94.7%	68.4%	63.2%	-
2. This approach is efficient	84.2%	52.6%	47.4%	0.041
3. This approach decreases extracurricular work	31.6%	36.8%	78.9%	0.006
4. This approach makes learning more targeted and more interesting	89.5%	63.2%	31.6%	0.001
5. This approach enhances my ability to analyze and solve problems	94.7%	57.9%	36.8%	< 0.001
6. This approach helps me master theoretical knowledge	73.7%	42.1%	52.6%	0.136
7. This approach helps me improve clinical skills	84.2%	36.8%	31.6%	0.002
8. This approach facilitates clinician-patient communication	84.2%	26.3%	21.1%	< 0.001

2. Theory test

Following the training, students undertook a final examination consisting of six items, namely the key anatomical structure of the maxillary sinus, indications for different sinus lifting techniques, biological principle of LWSA, the appropriate bone graft material of LWSA, the success rate of LWSA and management of complications. The total score was 60 points, 10 points for each question.

3. Case analysis

After the theory test, the teacher presented a new case for LWSA with detailed information (medical history, clinical manifestations, and radiographic findings). Students were required to provide written responses to questions concerning diagnosis and treatment planning based on course content within a time limit. Finally, the papers were graded anonymously. The total score were 40 points, 5 points for each question.

Statistical analysis

Pearson’s chi-square test was employed to analyze student’ opinions regarding the teaching methods among the three groups. Theory and case analysis scores are presented as mean value ± standard deviation (SD). The Shapiro Wilk test was used to assess normality. The Kruskal-Wallis H was used to analyze the difference in scores among the three groups. The Kruskal-Wallis test was applied for subsequent pairwise comparison between groups. Data were analyzed with SPSS version 26.0. A P-value of < 0.05 was considered statistically significant for all two-sided tests.

Results

The longitudinal digital workflow of LWSA cases used in digital PBL-CBL method

Thirty LWSA cases using digital workflow with one to four teeth missing in the posterior maxilla were included for digital PBL-CBL method. These cases can cover all the techniques and theoretical knowledge in courses of LWSA. Ten patients revealed thickening of the maxillary sinus mucosa (Fig. 6A), seven had maxillary sinus cysts (Figs. 6B and 6C), and five had maxillary sinus septa (Fig. 6D). The fully digital workflow enables students to utilize the software's threshold segmentation and 3D reconstruction functions to achieve intuitive observation and measurement of anatomical structures, so as to understand the principles on how to make a bone grafting and implant design. In the presence of moderate mucosal thickening, virtual surgical planning at T0 demonstrated that LWSA could be performed directly without membrane manipulation, subsequently followed by a routine implant placement at T2 (Fig. 6E). For larger cyst, simultaneous enucleation was necessary during LWSA (Fig. 6F), whereas smaller cyst could be mobilized and elevated along with the sinus membrane (Fig. 6G). Maxillary sinus septa could be effectively avoided through digital planning at T0, and the adaptation of implant direction and position was then guided at T2 according to available bone volume (Fig. 6H).

At T1 and T2, leveraging fully digital data and software, students are able to visualize the results of bone augmentation at implant sites, perform detailed data analysis, and simulate implant placement, thus enabling precise planning of subsequent surgical steps. For example, one patient showed inadequate new bone height at the implant site at T2 and underwent second transcrestal sinus lifting simultaneously with dental implant placement at T3. One patient showed inadequate bone width at the implant site at T2 (Fig. 6I) and underwent guided bone regeneration simultaneously with dental implant placement at T3. With the help of digital data, students can better understand the necessity of performing a simultaneous second bone grafting procedure when planning the implant surgery (Fig. 6I). Four patients underwent nose bleeding, headache or infection in the first month after LWSA. One implant failed during the final restoration (Supplementary Material 1). Cases processed with a fully digital workflow can clearly and intuitively demonstrate the radiographic and histological features indicative of implant failure in unsuccessful cases.

Digital PBL-CBL vs Traditional PBL-CBL/ didactic teacher-centered method

This study included 57 students (24 men and 33 women) aged between 25 and 31 years (mean: 27.4 years). All students completed all scheduled sessions. No significant difference was found among the three groups in terms of gender or age. All the students complied with the schedule and attended lectures or discussions on time.

Table 1 presents the satisfaction rates for the different teaching methods evaluated in this study. The traditional PBL-CBL group reported higher satisfaction than the control group on most surveyed items, with the exception of “This approach decreases extracurricular work” and “This approach helps me master theoretical knowledge” (Fig. 7). This indicated that the traditional PBL-CBL method may add to students’ extracurricular workload and did not demonstrate an advantage in facilitating theoretical knowledge acquisition. The digital PBL-CBL method, which employed fully digital workflow case presentations, achieved higher satisfaction ratings than the other two groups across all items except for “This approach decreases extracurricular work” (Fig. 7). The traditional and digital PBL-CBL groups reported similar perceptions (traditional PBL-CBL: 31.6%, digital PBL-CBL: 36.8%) regarding the extent of extracurricular workload. However, statistically significant differences between the two PBL-CBL groups were observed in items related to “This approach enhances my ability to analyze and solve problems”, “This approach helps me improve clinical skills” and “This approach facilitates clinician-patient communication” (Fig. 7). Furthermore, compared to the control group, the digital PBL-CBL group showed significantly higher satisfaction across all items, except for“This approach helps me master theoretical knowledge”(Fig. 7). These findings suggest that the digital PBL-CBL method is particularly more effective in enhancing students' practical thinking, clinical problem-solving and communication abilities.

Table 2 presents the scores of the theory test and the case analysis. The digital PBL-CBL group achieved the highest mean scores in both theory test (48.44 ± 8.10) and case analysis (33.50 ± 5.34), resulting in the highest total score (81.94 ± 8.93) (Fig. 8). All differences were all statistically significant when compared to the traditional PBL-CBL and control groups (Fig. 8). Although the traditional PBL-CBL method obtained higher scores than the control group in both the theory test and case analysis, the difference in theory test scores did not reach statistical significance (Fig. 8). Collectively, these findings highlight the specific efficacy of the digital PBL-CBL teaching method in improving the mastery of theoretical knowledge, practical thinking and clinical problem-solving abilities.

Table 2
Comparison of average scores of the three groups (n = 19)

Group	Theory Test	Case Analysis	Total Score
Digital PBL-CBL(n = 19)	48.44 ± 8.10	33.50 ± 5.34	81.94 ± 8.93
Traditional PBL-CBL(n = 19)	39.28 ± 10.88	27.78 ± 4.24	67.06 ± 10.66
Control(n = 19)	38.44 ± 10.44	18.50 ± 7.41	56.94 ± 12.80
Kruskal-Wallis H	9.950	27.805	26.658
P-value	< 0.01	< 0.01	< 0.01

The extra concrete examples of Digital PBL-CBL teaching method

Two undergraduate students who have been trained by digital PBL-CBL method won the University-level and Municipal-level Outstanding Undergraduate Thesis Prizes respectively. Four postgraduate students delivered presentations at the FDI international academic conferences and the Annual Meeting of the Chinese Society of Oral Implantology in 2025. The ability to critically think, analyze and solve real problems and their communication skills have been cited as the inclusion criteria for the conference. One of the students won Excellence Award in the clinical case competition of the Annual Meeting of the Chongqing Society of Oral Implantology in 2025. The competition requires participants to present clinical studies or case reports of implant dentistry through PowerPoint presentation within a specified time. These students trained with digital PBL-CBL method achieved excellent results in the competition and conferences, illustrating the effectiveness of the digital PBL-CBL method.

Discussion

The present study successfully established a longitudinal digital workflow dedicated to LWSA. With the digital workflow, the digital PBL-CBL method demonstrated significant advantages over the traditional PBL-CBL in teaching LWSA. Student evaluations consistently reflected a strong preference for the digital method, highlighting its benefits in improving learning efficiency and targeting, clinical skills, and clinician-patient communication. This subjective superiority was objectively validated by the significantly higher scores achieved by the digital PBL-CBL group in theoretical tests and case analysis compared to the other two groups. These findings suggest that the digital PBL-CBL method represents an effective pedagogical evolution for teaching complex surgical techniques such as LWSA.

Previous research demonstrated that the PBL-CBL had great potential to enhance theoretical knowledge acquisition than using PBL or CBL alone [23–25]. However, the traditional PBL-CBL method demonstrated no significant advantage over didactic teacher-centered method in conveying theoretical knowledge in the present study. This contradiction may be caused by the greater anatomical and technical complexity required for LWSA. The traditional PBL-CBL method, which primarily relied on two-

dimensional CBCT images and pictures, failed to convey an intuitive understanding of anatomical variations and surgical procedures. When digital workflow was integrated with the traditional PBL-CBL, abstract anatomy was converted into interactive three-dimensional visualizations through reconstruction. Complex surgical procedures with limited access could be directly visualized via an endoscope. As the results, a higher proportion of students in the digital PBL-CBL group believed that this method facilitated their mastery of theoretical knowledge compared to the traditional PBL-CBL group, coupled with a correspondingly higher theory test score. The findings indicate that the comprehensive digital workflow of clinical cases can enable students construct a systematic and cohesive understanding of LWSA.

Studies have demonstrated that digital teaching methods in complex surgeries, such as thoracic and abdominal procedures, can not only enhance theoretical understanding but also effectively improve clinical critical thinking [26, 27]. Compared with other procedures in implant dentistry, LWSA presents significant technical challenges including the need for 3D navigation of variable sinus structures, meticulously managing the thin sinus membrane, and precise bone grafting in a confined, low-visibility space. The traditional PBL-CBL method, constrained by the limited clinical observation is fundamentally inadequate for attaining these competencies. The digital longitudinal digital workflow established in this study enabled data-driven surgical simulation for personalized preoperative planning though 3D reconstruction. Furthermore, it facilitates the correlation of radiographic and histologic findings with postoperative surgical outcomes. As shown in the results, students in the digital PBL-CBL group demonstrated substantial improvements in problem analysis and solving abilities and significant higher scores of case analysis compared to other groups. Taken together, the digital PBL-CBL method can effectively promote proactive decision-making in complex, multi-stage clinical procedures.

Digital teaching is shifting surgical training from a time-based experience-driven model to a data-driven framework [28, 29]. This shift utilizes data to enable personalized learning, promotes quality through resource sharing, and ultimately contributes to a safer, more efficient educational resource. The longitudinal digital workflow in the present study provides a solid foundation for future development of shared resource platform for LWSA. While promising, this study has limitations that must be acknowledged. First, the digital teaching workflow currently depends on multi-software data conversion, which increases the teacher’s learning burden. Second, the evaluation lacks hands-on sessions, limiting the assessment of practical skill development. Third, the absence of long-term follow-up data hinders the demonstration of postoperative outcomes. In future work, we plan to develop dedicated teaching software that integrates the digital workflow into hands-on training modules, and enrich the digital cases both longitudinally and horizontally to achieve comprehensive coverage of clinical scenarios.

Conclusion

In conclusion, this study demonstrates that the integration of a longitudinal digital workflow with the digital PBL-CBL teaching method presents an effective model for teaching high-stakes procedures like LWSA. Despite its limitations, this "data-driven" and immersive teaching method establishes a promising

framework for standardizing, securing, and enhancing skill acquisition in oral surgery training, while also laying a foundation for future technological integration and educational research.

Declarations

Institutional Ethics Approval:

This study received approval from the Ethics Committee of the Affiliated Stomatological Hospital of Chongqing Medical University (Approval No. xyjg220209) and was conducted in compliance with the ethical principles of the Declaration of Helsinki.

Informed Consent

Statement:

Informed consent

was obtained from all subjects involved in the study.

Consent for publication

Written informed consent was obtained from all patients for the publication of their images in the figures. The images have been fully anonymized, and no personally identifiable information is disclosed.

Conflicts of Interest:

No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication.

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Author Contribution

Y.X. performed the experiments, analyzed the data, prepared figures and/or tables and drafted the manuscript. K.T. performed the experiments, responsible for the establishment of digital workflow and human sample collection. H.Y collected and curated the data. Q.W. conceived and designed the experiments, supervised all aspects of the study and served as the corresponding author. All authors read and approved the final manuscript.

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Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

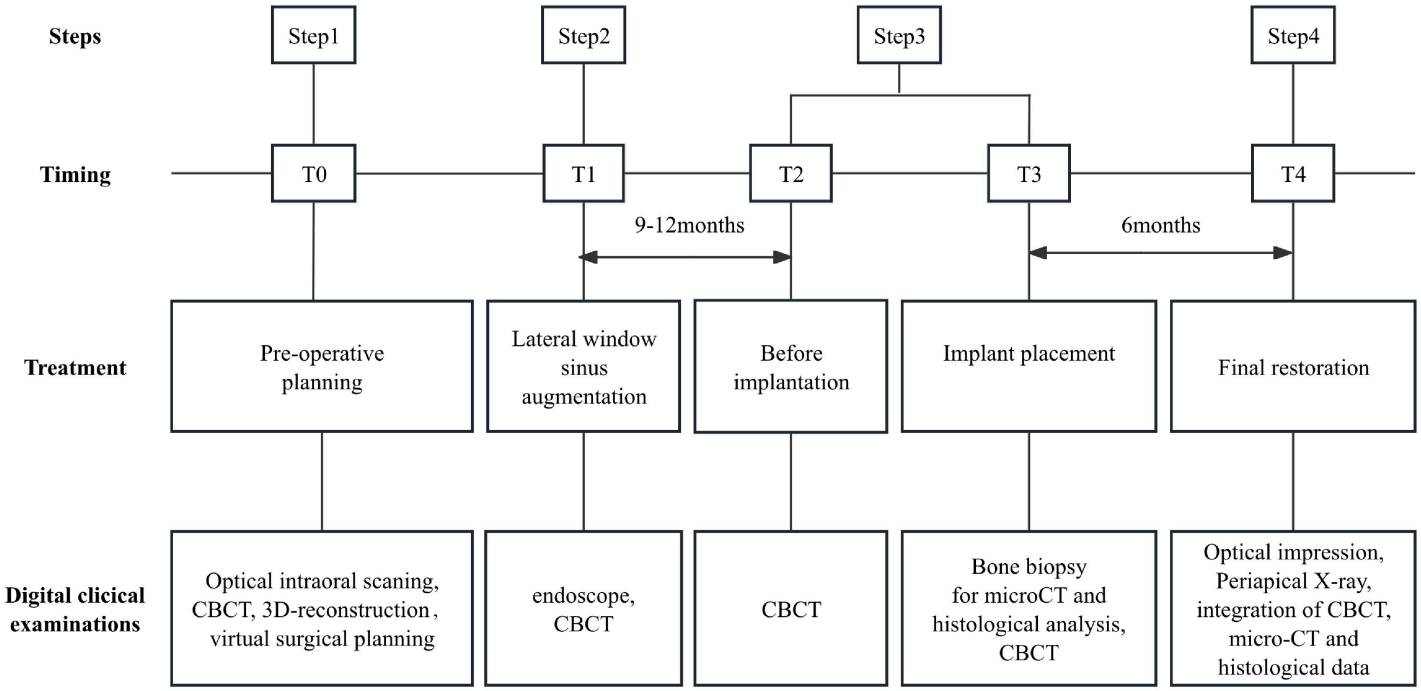


Figure 1

Steps of digital workflow for LWSA cases.

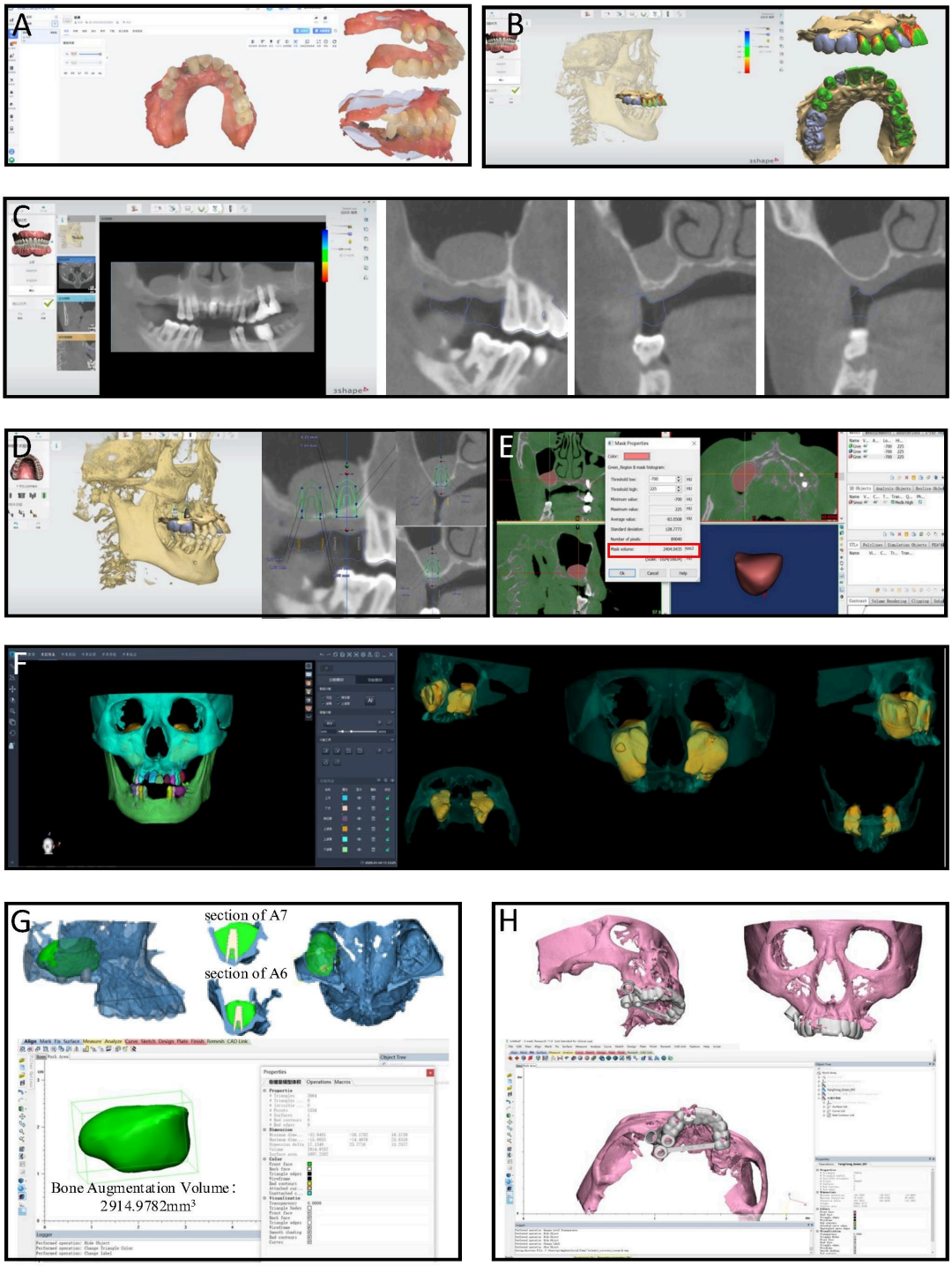


Figure 2

The preoperative digital data and virtual LWSA plan. (A) The patient's intraoral scan. (B) Virtual teeth arrangement. (C) Preoperative CBCT revealed severely resorbed alveolar bone with a large cyst in the maxillary sinus floor. (D) Virtual implant placement and parameter measurements based on the intraoral scan and CBCT image. (E) Intuitive visualization and measurement of the cyst using 3DSlicer 4.10.2 software. (F) The three-dimensional anatomical morphology of the maxillary sinus was segmented and

visualized directly through the surgical navigation software. (G) Calculate the volume and distribution of bone substitutes virtually. (H) A surgical guide for LWSA was designed based on the virtual design.

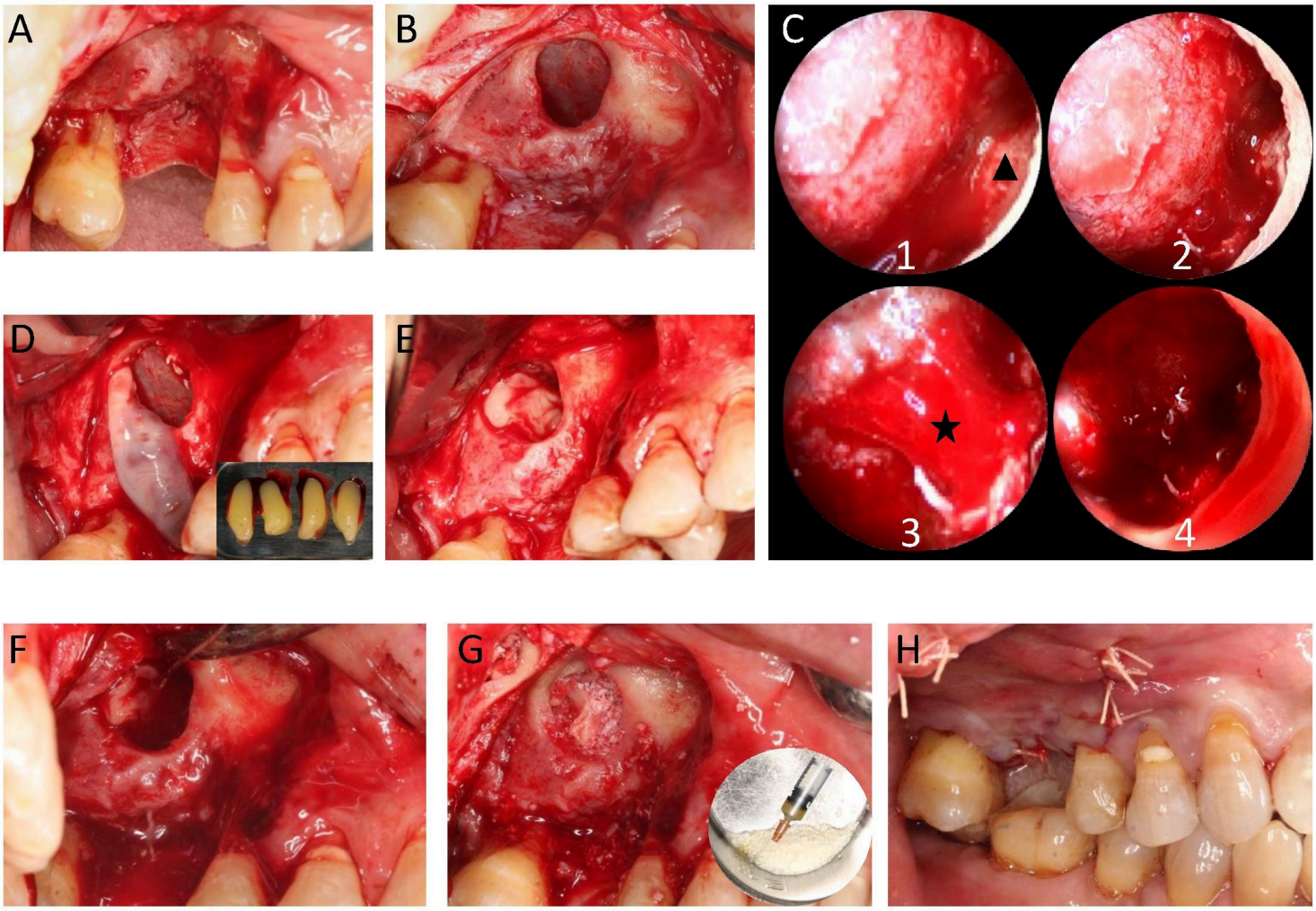


Figure 3

The surgical procedures for LWSA. (A) Flap reflection revealed lateral maxillary wall. (B) A bony window was created. (C) The Schneiderian membrane was examined by an endoscope. (C1) Residual bone fragments on the maxillary sinus mucosa and a prominent bony ridge were observed. Black triangle, bony ridge. (C2) Meticulous dissection beyond the ridge. (C3) Mucosal adhesions were encountered. Black star, adhesions. (C4) Adhesions were meticulously separated to achieve complete elevation of sinus membrane. (D) and (E) Place concentrated growth factors (CGF) beneath the sinus membrane to reduce perforation. (F) The space between CGF and the original sinus floor bone. (G) The created space was compactly filled with the sticky bone graft, a mixture of deproteinized bovine bone, and injectable platelet-rich-fibrin. (H) Close the wound with no tension.

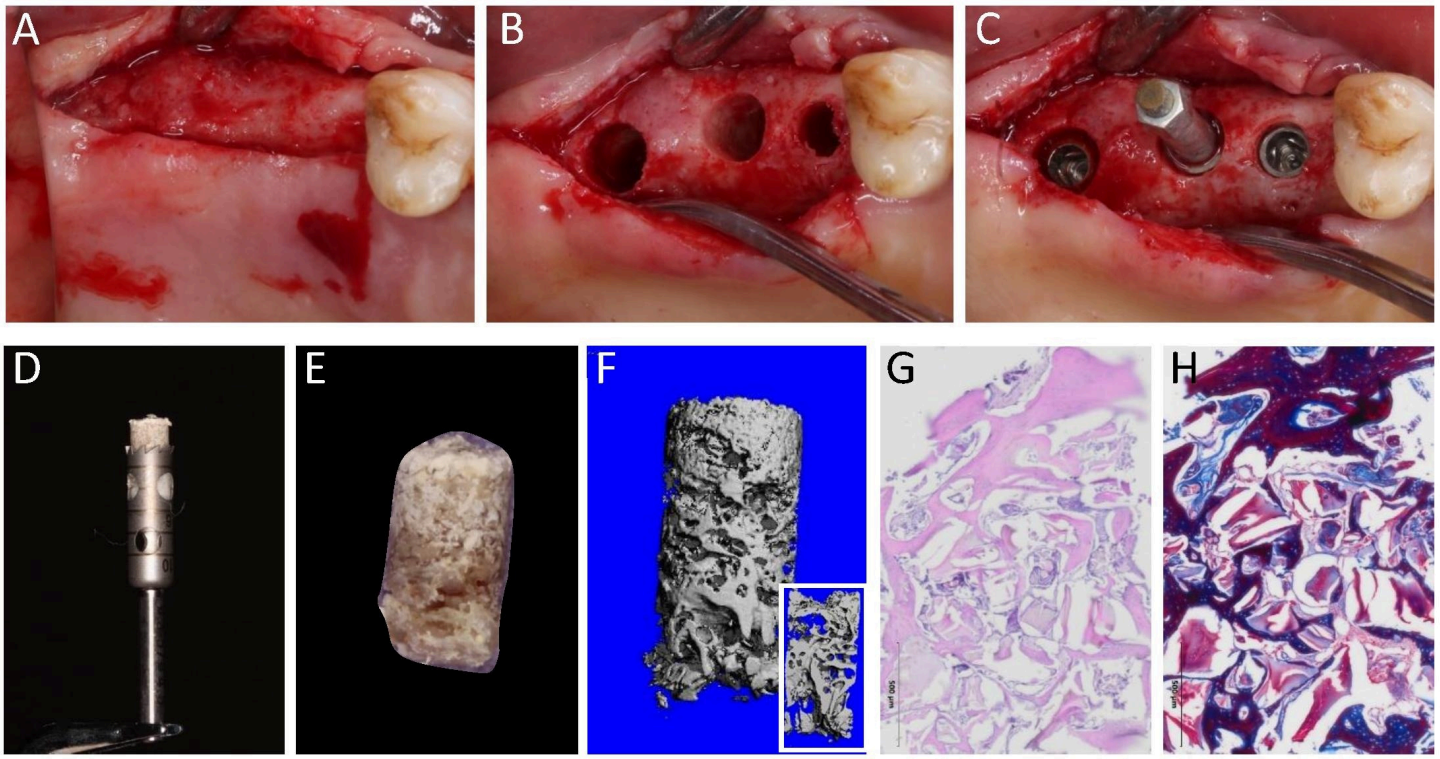


Figure 4

The implant placement and acquisition of microCT and histological data of the augmented bone. (A) Flap elevation. (B) Prepare the implant osteotomies. (C) Place the implants as designed. (D) A trephine drill was used to collect a biopsy at the implant site. (E) The core bone biopsy. (F) Micro-CT analysis, (G) H&E staining, and (H) Masson's trichrome staining of the biopsy all demonstrated favorable bone regeneration.

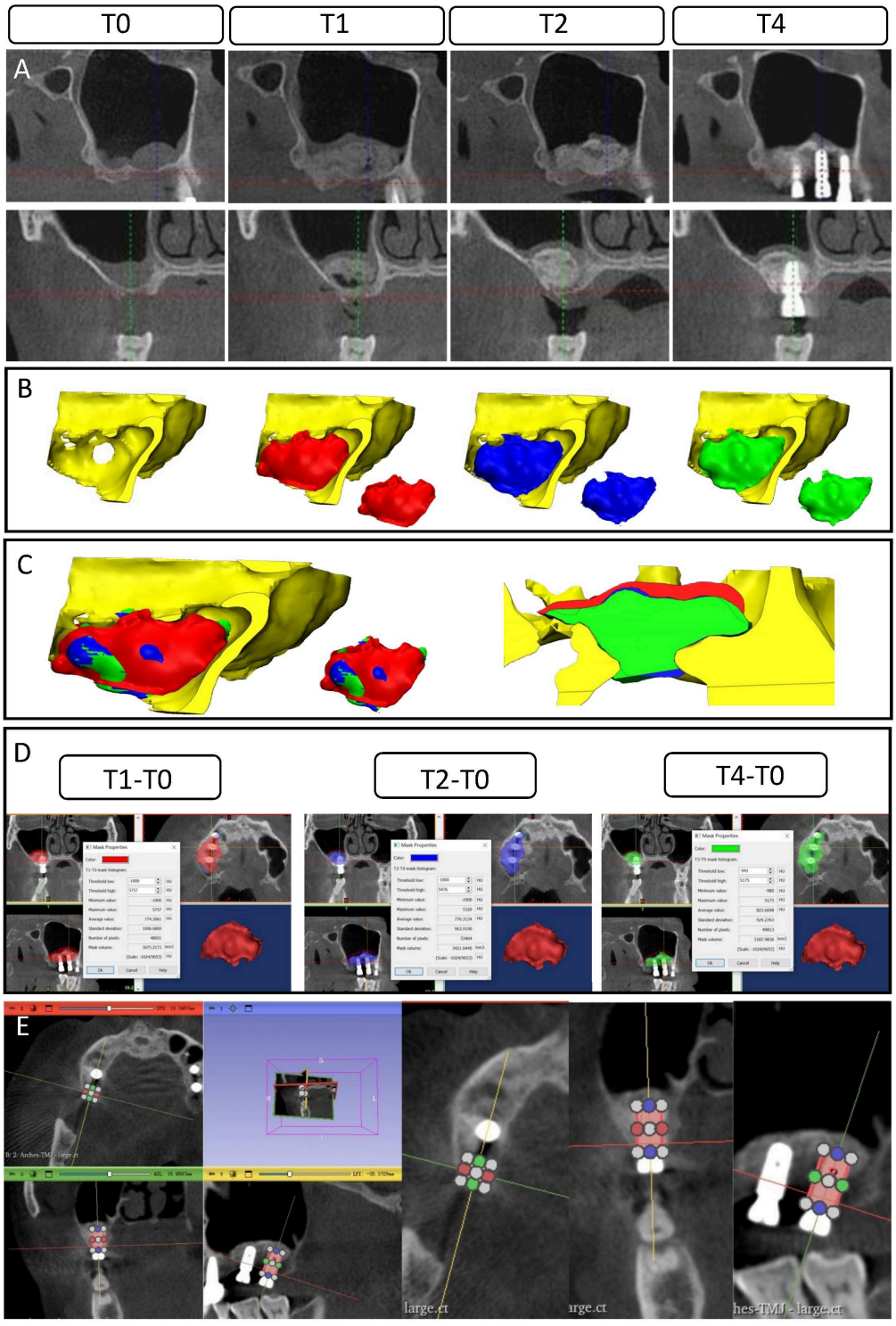


Figure 5

Integration of digital data. (A) Longitudinal CBCT evaluations at different time points. Preoperatively (T0), immediately after LWSA (T1), before implantation (T2), and 6 months after implant placement (T4). (B) The reconstructed 3D jawbone models and the augmented bone at different time points. (C) The superimposition of the augmented bone contour to show changes in volume and shape. (D) Mineral

density changes compared to T0 via 3DSlicer 4.10.2 software. (E) Mark the location of the biopsy by superimposing reconstructed models at T2 and T3 via 3DSlicer 4.10.2 software.

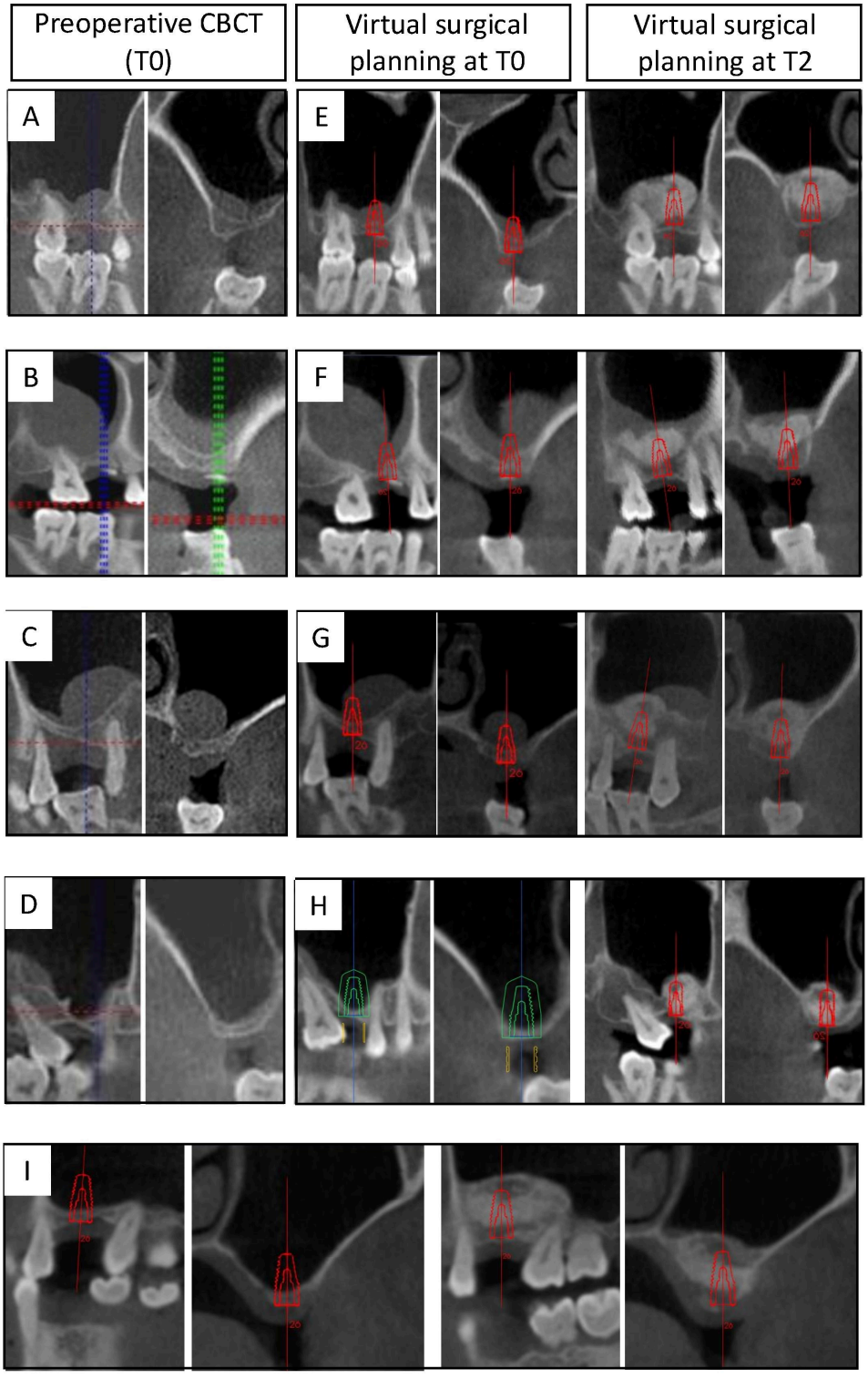


Figure 6

The longitudinal digital workflow and personalized virtual surgical planning of LWSA cases. (A) Mucosal thickening, (B) and (C) sinus, and (D) septa in the maxillary sinus. (E) LWSA would be performed

directly without membrane manipulation despite mucosal thickening. (F) The larger cyst would be enucleated concurrently with LWSA. (G) The smaller cyst would be elevated along with the sinus floor. (H) Septa could be effectively avoided by digital planning. (I) A simultaneous second bone grafting procedure was required with inadequate bone width after LWSA. T0, preoperatively. T2, before implantation.

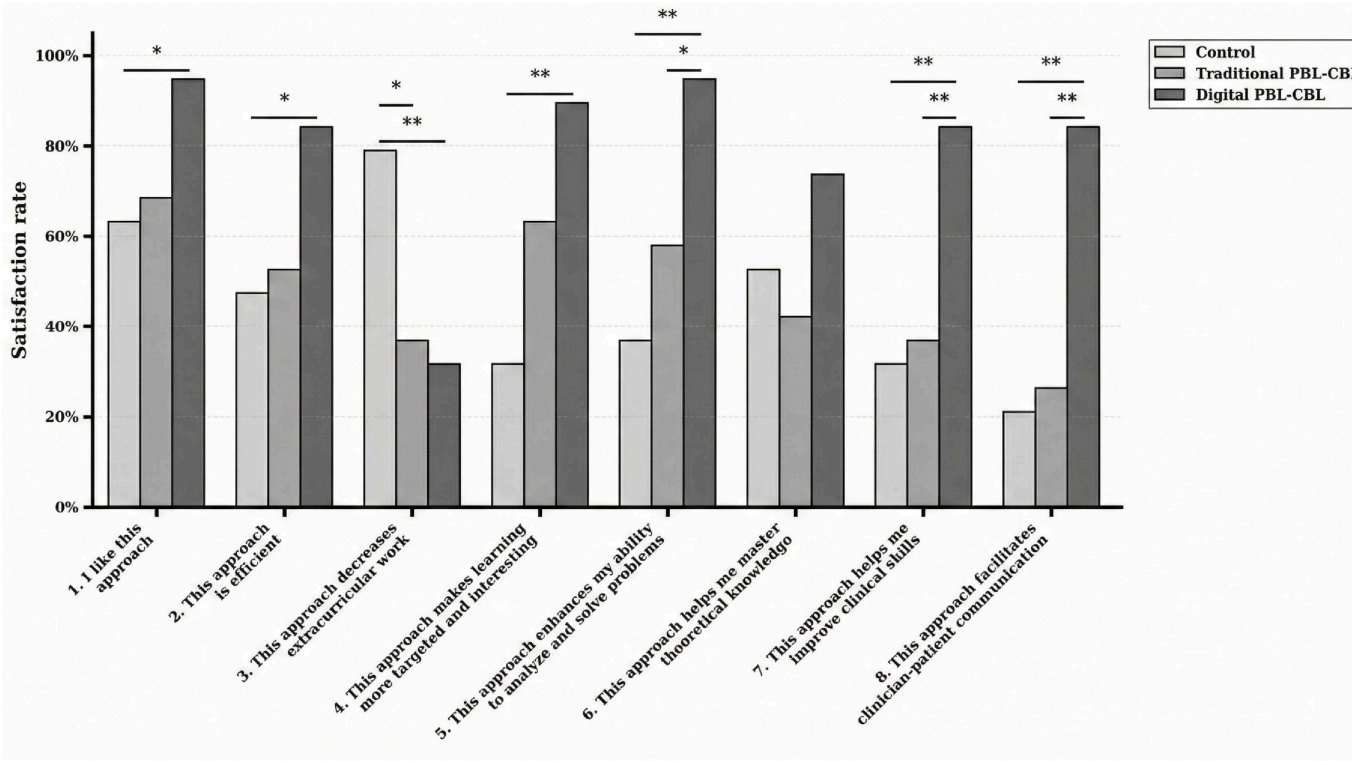


Figure 7

Rate of satisfaction with the three teaching methods. **P<0.01, *P<0.05.

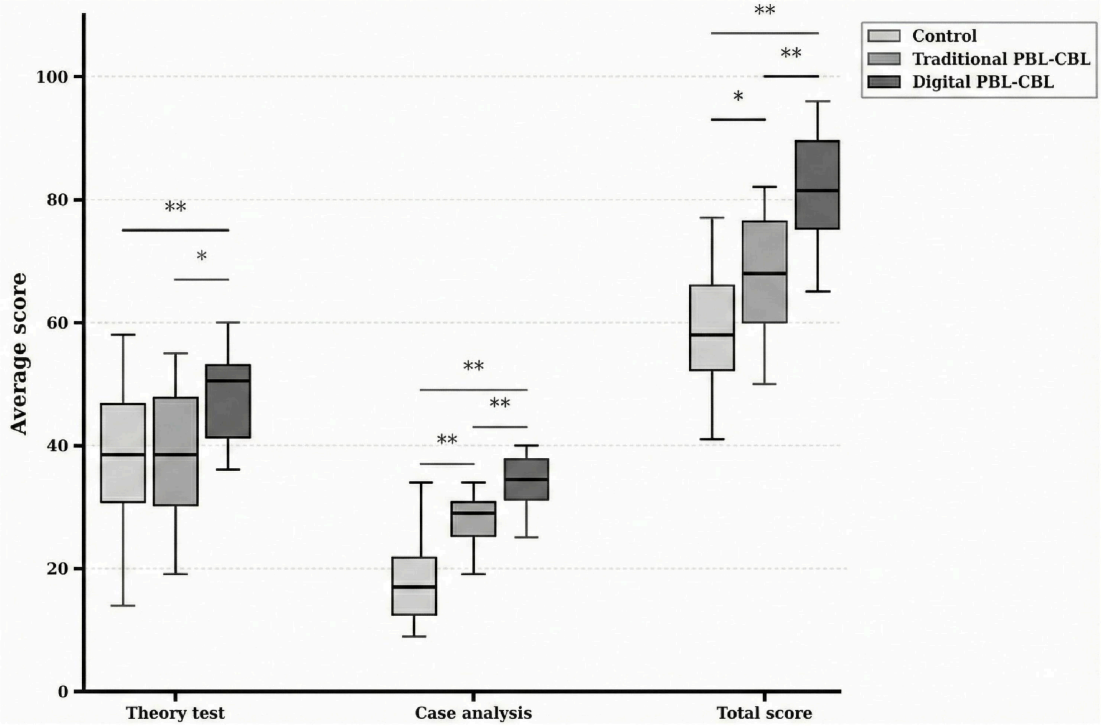


Figure 8

Score of theory test, case analysis and the two combined. **P<0.01, *P<0.05.

Supplementary Files

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- SupplementaryMaterial1.pptx