Modular Preoperative Planning Software for Computer-Aided Oral Implantology and the Application of a Novel Stereolithographic Template: A Pilot Study

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ABSTRACT

Purpose: In the field of oral implantology, there is a trend toward computer-aided implant surgery, especially the application of computerized tomography (CT)-derived surgical templates. However, because of relatively unsatisfactory match between the templates and receptor sites, conventional surgical templates may not be accurate enough for the severely resorbed edentulous cases during the procedure of transferring the preoperative plan to the actual surgery. The purpose of this study is to introduce a novel bone–tooth-combined-supported surgical guide, which is designed by utilizing a special modular software and fabricated via stereolithography technique using both laser scanning and CT imaging, thus improving the fit accuracy and reliability.

Materials and Methods: A modular preoperative planning software was developed for computer-aided oral implantology. With the introduction of dynamic link libraries and some well-known free, open-source software libraries such as Visualization Toolkit (Kitware, Inc., New York, USA) and Insight Toolkit (Kitware, Inc.) a plug-in evolutive software architecture was established, allowing for expandability, accessibility, and maintainability in our system. To provide a link between the preoperative plan and the actual surgery, a novel bone–tooth-combined-supported surgical template was fabricated, utilizing laser scanning, image registration, and rapid prototyping. Clinical studies were conducted on four partially edentulous cases to make a comparison with the conventional bone-supported templates.

Results: The fixation was more stable than tooth-supported templates because laser scanning technology obtained detailed dentition information, which brought about the unique topography between the match surface of the templates and the adjacent teeth. The average distance deviations at the coronal and apical point of the implant were 0.66 mm (range: 0.3–1.2) and 0.86 mm (range: 0.4–1.2), and the average angle deviation was 1.84° (range: 0.6–2.8°).

Conclusions: This pilot study proves that the novel combined-supported templates are superior to the conventional ones. However, more clinical cases will be conducted to demonstrate their feasibility and reliability.

KEY WORDS: computer-aided surgery, oral implantology, preoperative planning, stereolithographic template

INTRODUCTION

During the past decades, the introduction of implant dentistry has initiated a revolution in oral rehabilitation for both partially and fully edentulous patients. Nowadays, the clinical application of the concept of osseointegration reveals a predictable long-term success. However, improper implant placement has a profound and often detrimental effect on the long-term predictability and success of the implant-supported prosthesis.[1–4]

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Because the traditional surgical templates are manufactured on the basis of the panoramic radiographic image, which, however, is limited by its characteristic magnification and distortion as well as the associated lack of image sharpness, it may lead to inaccuracy and fallibility of the preoperative planning for dental implant placement.[5] Currently, more and more studies focus on the research of computerized tomography (CT)-based computer-guided oral implantology, which can be divided into two different groups: high precision technologic tools (surgical guides or templates), with which to transfer the preoperative planning based on CT data to the actual surgical site,[3,4,6–14] and intraoperative surgical navigation system, with an optical or magnetic tracking device.[15–20] As for the CT-derived surgical guides, several CAD/CAM systems for preoperative planning and the fabrication of surgical guides have been developed and are commercially available, including:

1. SimPlant® (Materialise, Leuven, Belgium)[3,4,6,7];
2. NobelGuide® (Nobel Biocare, Yorba Linda, CA, USA)[8,9];
3. coDiagnostiX® (IVS-Solutions AG, Chemnitz, Germany)[10];
4. ImplantMaster™ (I-Dent Imaging, Ft. Lauderdale, FL, USA)[11];
5. Med3D® (med3D AG, Zurich, Switzerland)[10];
6. Vimplant™ (CyberMed Inc., Seoul, Korea) (http://www.4biomed.com/v-implant.asp?cid=9&pid=30).

With respect to intraoperative surgical navigation, the following computer-aided systems have been presented in the literature:

1. VISIT (Department of Biomedical Engineering and Physics, University of Vienna, General Hospital, Vienna, Austria)[15,16];
2. IGI™ (DenX, Jerusalem, Israel)[17];
3. RoboDent® (RoboDent GmbH, Berlin, Germany)[18,19];
4. Stryker Leibinger™ (Stryker Leibinger, Freiburg, Germany).[20]

These two approaches have their own advantages and disadvantages. Although navigation gives more freedom and flexibility for the surgeon to modify the planned position of the implants, it is more prone to human error and less accurate than surgical guides.[21] Another advantage of surgical guides is convenience and ease of use; therefore, they are relatively prevalent in the research of computer-guided oral implantology.

Once the treatment planning is completed with the application of preoperative planning software, surgical guides can be produced using a rapid prototyping technology called stereolithography. The drill guides dictate the location, angle, and depth of insertion of the implant, so as to provide a link between the planning and the actual surgery by transferring the simulated plan accurately to the patient. Actually, there are three types of surgical guides, that is, bone supported, mucosa supported, and tooth supported.[3,4,7] As far as conventional clinical cases are concerned, the template might be relatively stably placed on the underlying tissue such as the jawbone or mucosa. However, with regard to some complex cases involving severely resorbed edentulous cases, clinical experience demonstrates that fixture of the surgical guides (especially for bone-supported or mucosa-supported ones) is not so stable because of unsatisfactory match between the templates and receptor sites. Problems will occur as even a slightest angular error may result in significant positional errors at the end of the tool trajectory.[22]

The purpose of this study is to introduce a novel bone–tooth-combined-supported surgical guide for implant placement. With the use of a three-dimensional laser scanner, more detailed surface information at the level of the dentition can be obtained. Then, fusion of laser-scanned dental occlusion data and CT data is realized through an image registration technique. On the basis of this fusion of data and preoperative planning information, a three-dimensional computer model of this kind of bone–tooth-combined-supported surgical guides can be designed by utilizing a special software and, finally, fabricated via stereolithography technique. The hypothesis is that this approach is achieved using both laser scanning and CT imaging, thus improving the fit accuracy and reliability of this sort of surgical guides.

MATERIALS AND METHODS

The Preoperative Planning Software

In response to the requirement of oral implantology, we built a software called Computer-Assisted Preoperative Planning for Oral Implant Surgery (CAPPOIS), which was divided into the following five modules:

1. The module for image importing and three-dimensional reconstruction: Original CT image

data in Digital Imaging and Communications in Medicine (DICOM) file format can be imported. The image grayscale and contrast can be adjusted, the bone can be segmented from its neighboring areas including soft tissue, water, adipose, etc., and then a three-dimensional cranio-maxillofacial model can be reconstructed and rendered.

2. The module for multiplanar reconstruction: A panoramic curve following the curvature of the jawbone on one of the imported axial CT image slices can be drawn manually; then, on the basis of this panoramic curve, the series of panoramic images and cross-sectional images can be reconstructed. With respect to a plan of the mandible type, several points of inferior alveolar nerves can be labeled according to the series of panoramic images, and then these nerves can be reconstructed and highlighted in the three-dimensional view.
3. The module for basic operations in two-dimensional/three-dimensional views: Translation, rotation, and zooming in and out of the two-dimensional/three-dimensional views can be done interactively. Three-dimensional cranio-maxillofacial models can be rendered, and the transparency of the models can be adjusted. In addition, geometric measurement can also be realized in the two-dimensional/three-dimensional views; for example, after selecting the required anatomic landmarks on the cranio-maxillofacial model, the distance between any two points and the angle among any three points can be calculated.
4. The module for implant design and adjustment: A certain type of virtual implants can be selected from an implant system library including Brånemark, ITI, FRIALIT, AVANA, Replace, Camlog, etc., and placed into the ideal areas in a two-dimensional/three-dimensional view. The position and orientation of the implant can be adjusted, taking into account prosthetic requirements and available local bone. If the information of an implant is changed on a two-dimensional/three-dimensional view, its information in all the other views will be updated simultaneously. Distance between an implant and alveolar nerves can be calculated, and collision detection among implants and bone density analysis around an implant can be done as well. In addition, relevant abutments and dentures can be designed.
5. The module for graphic user interfaces (GUIs): Export/import, redo/undo, storage, retrieval, and deletion of the preoperative planning data can be realized. The preoperative planning information can be saved and exported in a special file format, so that it can be used in the subsequent software for the design of surgical templates.

After comprehensively analyzing the above-mentioned functions, we designed the architecture of the software (shown in Figure 1). The key technology of the software involved some algorithms in the field of medical image processing and computer graphics. The major algorithms included DICOM file parsing, image segmentation and three-dimensional visualization,[23,24] spline curve generation, multiplanar reconstruction, spatial search and three-dimensional distance computing,[25] cutting,[25] volume measurement,[26,27] etc. For each of the algorithms, we developed a set of dynamic link libraries (DLLs) using Microsoft Visual C++, as well as the Visualization Toolkit (VTK, an open-source, freely available software system for three-dimensional computer graphics, image processing, and visualization, etc., http://www.vtk.org/) and Insight Toolkit (ITK, an open-source software toolkit for performing registration and segmentation, http://www.itk.org/) via object-oriented programming methodology; therefore, a three-layer modular software model was developed (shown in Figure 2). This basis can be extended by virtually any new approach or algorithm, which then becomes seamlessly integrated into the method set of the preoperative planning software framework. The aim is to provide well-defined levels of abstraction (the hiding of implementation details) from the individual components, so that new technology can be incorporated into the system without a complete software rewrite. As for the GUIs, we chose Microsoft Foundation Class, because the Win32 API offered the greatest versatility in exploiting the features of Windows. The main interface of the software is shown in Figure 3.

The user interface and functions of CAPPOIS parallels SimPlant,[3,4,6,7] which is already commercially available; however, as the visualization and image processing algorithms involved in our software are developed using VTK and ITK, a plug-in evolutive software architecture is established, allowing for expandability, accessibility, and maintainability in our system. In addition, aiming to make the software simply accessible and fulfill the

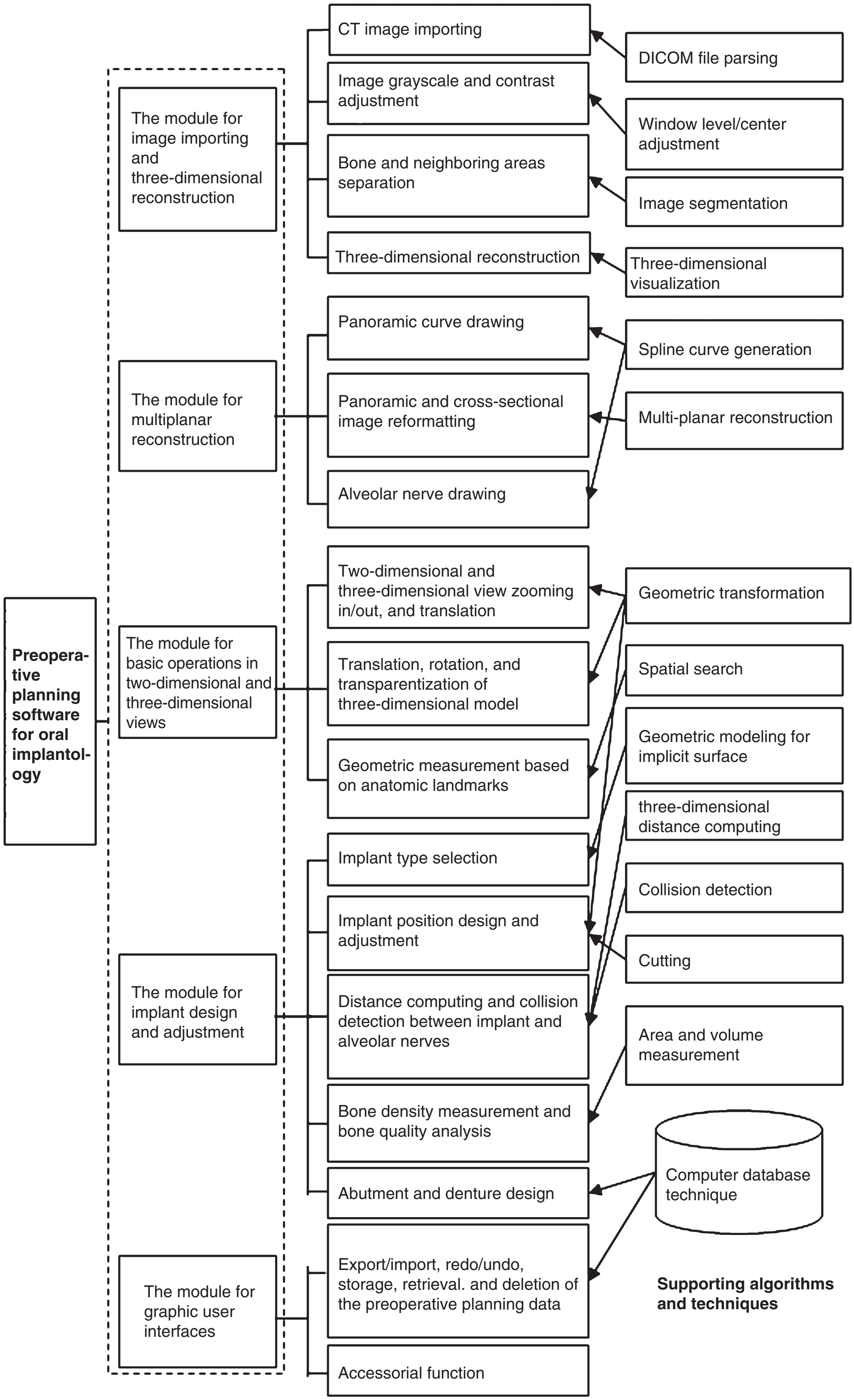

Figure 1 The architecture of the preoperative planning software for oral implantology. CT = computerized tomography; DICOM = Digital Imaging and Communications in Medicine.

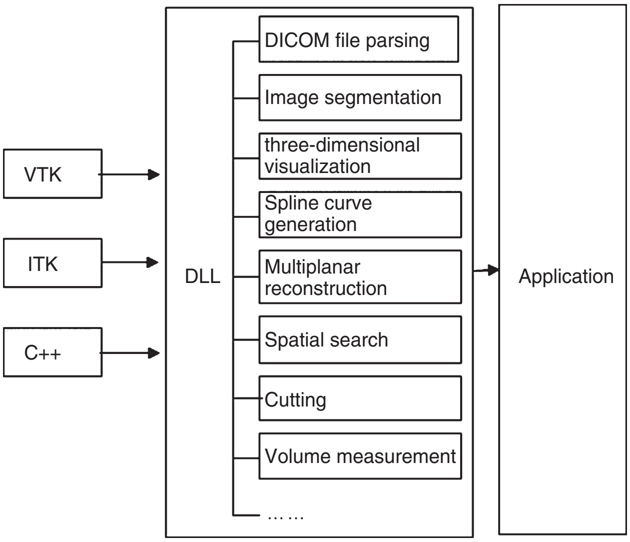

Figure 2 The three-layer modular software model. DICOM = Digital Imaging and Communications in Medicine; DLL = dynamic link library; ITK = Insight Toolkit; VTK = Visualization Toolkit.

research requirements in academia, our future work is to make CAPPOIS a free, open-source, and cross-platform (Windows, Linux, and Mac Os X operating systems) software for preoperative planning in oral implantology.

Registration

In order to produce a bone–tooth-combined-supported surgical guide, a detailed visualization of dentition is a prerequisite. However, a three-dimensional surface of the teeth created from the CT images of the patient is not accurate enough; furthermore, for the cases involving amalgam fillings, the streak artifacts jeopardize the details of the occlusion.[28] In this study, we presented a method of laser scanning combined with image registration technique to solve this problem.

At first, plaster casts of the patient were routinely made. These plaster casts were an accurate copy of the actual dentition of the patient.[28] Then, a commercially available, three-dimensional laser scanner was utilized

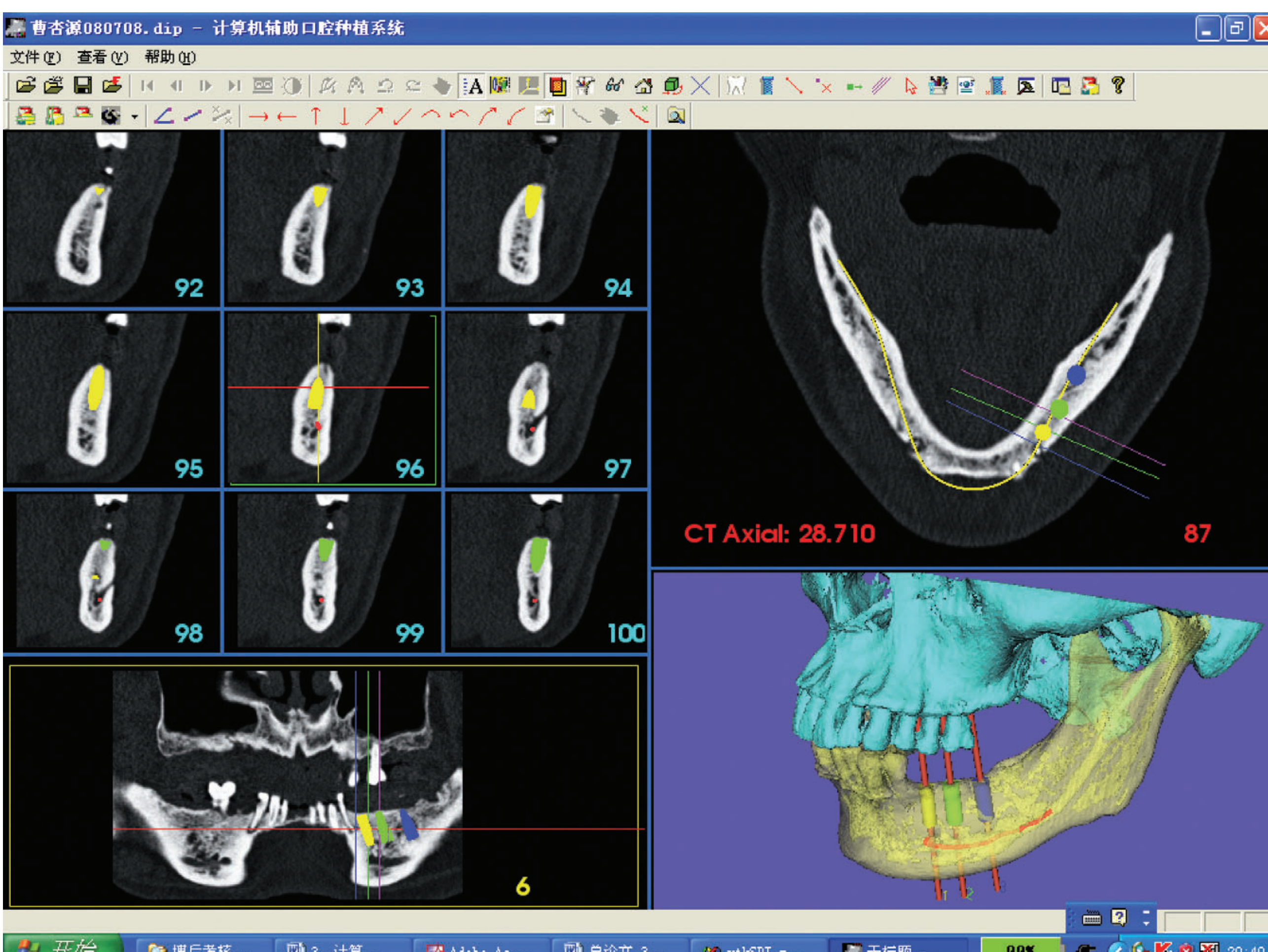

Figure 3 The main interface of the Computer-Assisted Preoperative Planning for Oral Implant Surgery.

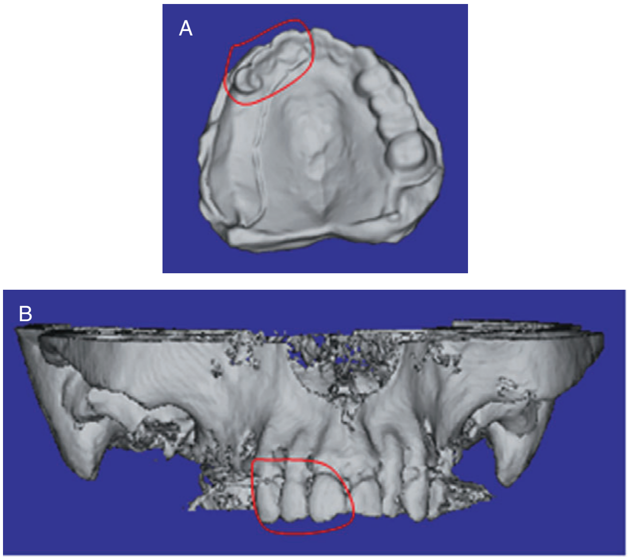

Figure 4 Three-dimensional reconstructed models respectively from the laser-scanned and computerized tomography (CT) data; the adjacent teeth (labeled in the enclosed red line area) in the edentulous region will be cut for registration. *A*, Three-dimensional model from the laser-scanned data. *B*, Three-dimensional model from the CT data.

to scan these plaster casts. The point cloud data acquired by the laser scanner were read and processed with 3DLaserRecon (a special software for laser-scanned data reconstruction developed by our institute; Institute of Biomedical Manufacturing and Life Quality Engineering, Shanghai Jiao Tong University, Shanghai, China). With the help of this software, data filtering and noise canceling were carried out, and then a three-dimensional digitized model of the dentition (shown in Figure 4A) could be reconstructed through radial basis functions algorithm.[29] The regions of interest, that is, the adjacent teeth surface in the edentulous region (shown in Figure 4), which matched the inner surface of surgical templates, were respectively cut from the laser-scanned model and the three-dimensional CT model, and then imported to MedRegCAD (a special software for image registration and surgical template design, developed by our institute; Institute of Biomedical Manufacturing and Life Quality Engineering, Shanghai Jiao Tong University, Shanghai, China) for registration.

Image registration refers to superimposing the three-dimensional laser-scanned dentition model onto the three-dimensional skull model reconstructed from CT images. A two-step method, respectively initial landmark registration and final surface registration, was used to accomplish this process, described as follows.

At first, at least three corresponding landmark pairs were indicated on the regions of interest: alternating between the three-dimensional laser-scanned model and the three-dimensional CT model (shown in Figure 5, A and B). Then, with the use of the singular value decomposition algorithm,[30] landmark registration

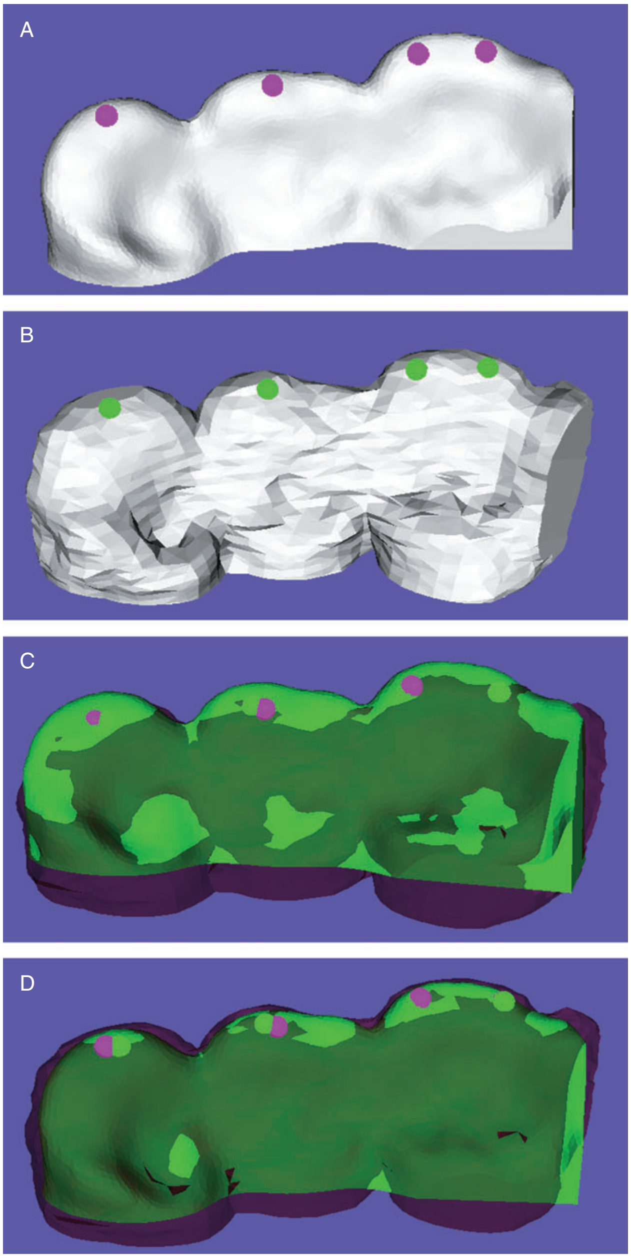

Figure 5 Registration procedure. The red and green dots represent corresponding landmark pairs; for C and D, the green and purple models respectively represent three-dimensional laser-scanned and computerized tomography (CT) models. *A*, The cut teeth from the three-dimensional laser-scanned model. *B*, The cut teeth from the three-dimensional CT model. *C*, The result from the landmark registration (first step). *D*, The result from the iterative closest point registration (second step).

(shown in Figure 5C) obtained the best fit, mapping one set of landmarks onto the other, in a least squares sense. After that, the second registration step was processed to match the two corresponding three-dimensional surfaces using the iterative closest point algorithm[31] (shown in Figure 5D). The core of the algorithm is to match each vertex in one surface with the closest surface point on the other, then apply the transformation that modifies one surface to best match the other (in a least square sense), and the proper convergence of the surfaces is finally obtained by iterating the procedure. The point of this two-step method is that the initial and final registration approaches are complementary. Landmark registration approximates the three-dimensional laser-scanned dentition model to the three-dimensional CT space. It serves as the basis on which surface registration improves the overall registration accuracy.

The Design and Manufacture of Surgical Templates

After registration, an "augmented" skull model with detailed dentition information was obtained (shown in Figure 6A). Then, with the use of MedRegCAD, the surface of the alveolar bone and adjacent teeth in the edentulous region was determined by drawing a closed spline curve along with the region manually. This two-dimensional surface was then extended to form a three-dimensional solid model through an approach using the tangent vectors at the edges of the surface.[32] On the basis of preoperative planning, a three-dimensional stereolithography model of the surgical template with cylindrical holes (shown in Figure 6, B–E) was then generated through boolean operation, that is, subtraction, between this solid model and the extended implants. Several windows with the shape of a hollow cylinder were designed on the buccal surface of the template to allow for irrigation with saline during the surgery (shown in Figure 6D). The implant surgery could be simulated in the software as well (shown in Figure 6F).

With respect to manufacturing, a rapid prototyping machine using the principle of stereolithography was employed to fabricate the resin surgical template (shown in Figure 6G). Finally, several surgical grade stainless steel tubes with suitable diameters were assembled to the cylindrical holes as metal sleeve guides in the template.

CLINICAL APPLICATIONS AND COMPARISON WITH BONE-SUPPORTED TEMPLATES

The advantages of this sort of surgical templates are demonstrated through clinical applications. In the following context, a clinical case is reported in detail, and then a comparison with bone-supported templates is described.

The general information about a severely resorbed edentulous patient is listed in Table 1. After the CT data of the patient were imported to CAPPOIS, the positions and orientations of the virtual implants were interactively designed to make optimal use of the bone volumes while protecting the critical anatomic structures, including the maxillary sinus, the nasal cavity, the adjacent tooth roots, etc. (shown in Figure 7), and then, this plan and the laser-scanned data of the patient's plaster cast were transferred to MedRegCAD for image registration and template design. Finally, the bone–tooth-combined-supported surgical guide, as well as the stereolithographic model of the patient's maxilla, was manufactured via rapid prototyping technology (shown in Figure 8, A and B).

On the day of the surgery, a mucoperiosteal flap was carried out after anesthesia, and then the template was stably placed on the alveolar bone as well as the adjacent teeth, allowing the stainless steel tube to help guide the osteotomy procedure (shown in Figure 8, C and D). The postoperative panoramic radiographic image (shown in Figure 9) demonstrated that all of the four implants were in ideal position and orientation, fulfilling anatomic and aesthetic requirements.

In order to make a comparison with the conventional bone-supported templates, clinical studies were conducted on four patients with similar edentulous areas. For each of them, four implants were planned to be inserted in the lateral distal extension area of the edentulous maxilla. One surgeon made preoperative planning and then performed osteotomies for all patients with the application of two different types of surgical guides. Bone-supported templates were used for patients 1 and 2, while our bone–tooth-combined-supported templates were used for the remaining two patients. After the placement of the implants, each patient was CT scanned, and then the postoperative images were aligned with the initial planning ones through an automatic image registration method using maximization of mutual information so that the overall accuracy could be calculated. Resulting deviations

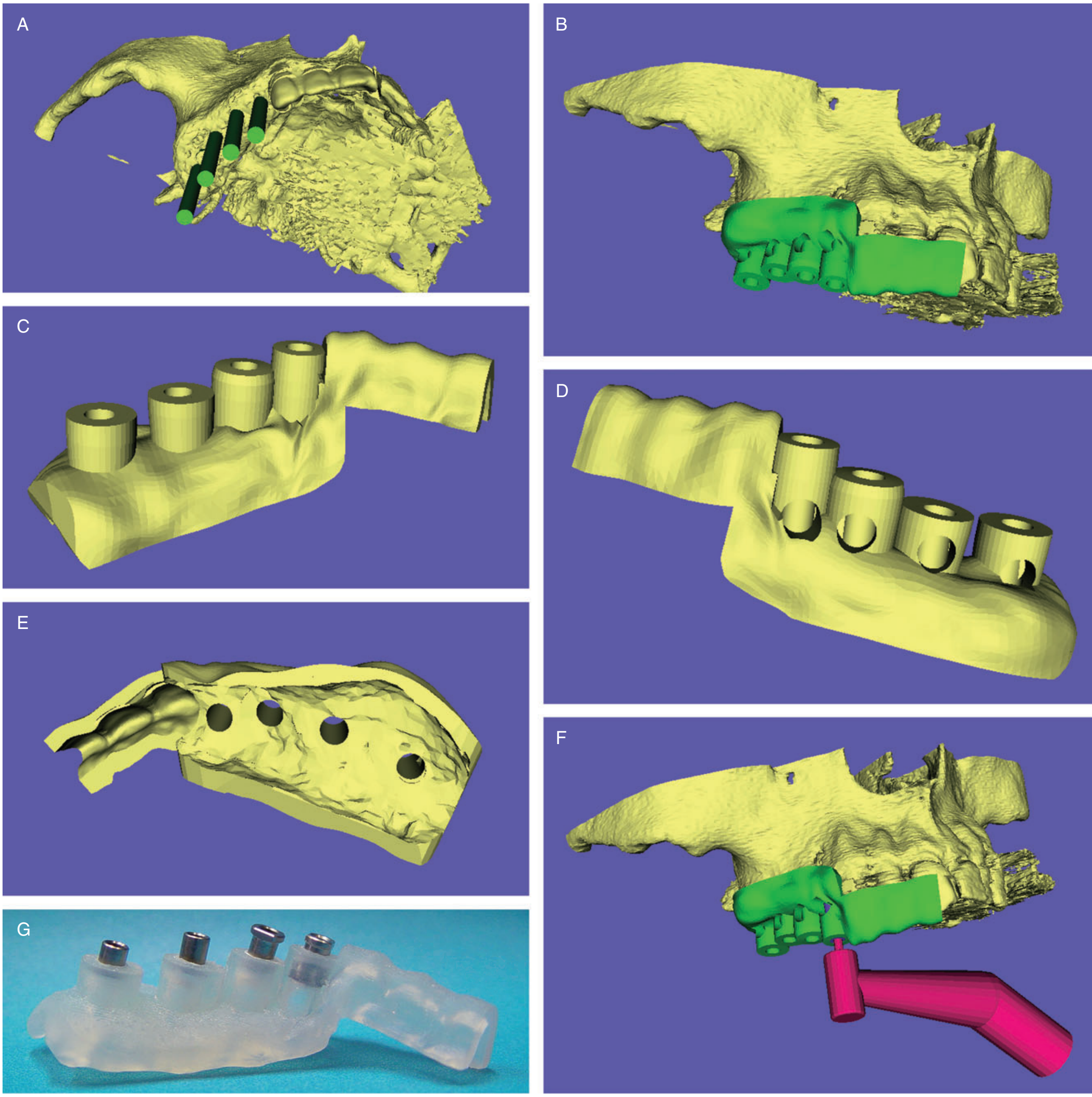

Figure 6 The CAD/CAM procedure of the surgical template. *A*, The "augmented" skull model with detailed dentition information. The green cylinders represent the extended implants. *B*, Three-dimensional model of the surgical template, created through boolean operation. *C*, Three-dimensional model of the surgical template, lingual side. *D*, Three-dimensional model of the surgical template, buccal side. *E*, Three-dimensional model of the surgical template, inner surface. *F*, Three-dimensional simulation of the implant surgery procedure. *G*, The resin surgical template fabricated through rapid prototyping technology, with several stainless steel tubes to be assembled.

TABLE 1 General Information about the Patient

Gender	Age	Indication	Prosthodontic Rehabilitation Method to Adopt
Male	60	Partially edentulous in the right posterior region of the maxilla	Four SCREW-LINE Promote® (CAMLOG, Basel, Switzerland) implants with a diameter of 5 mm and length of 13 mm in tooth positions 2, 3, 4, and 5

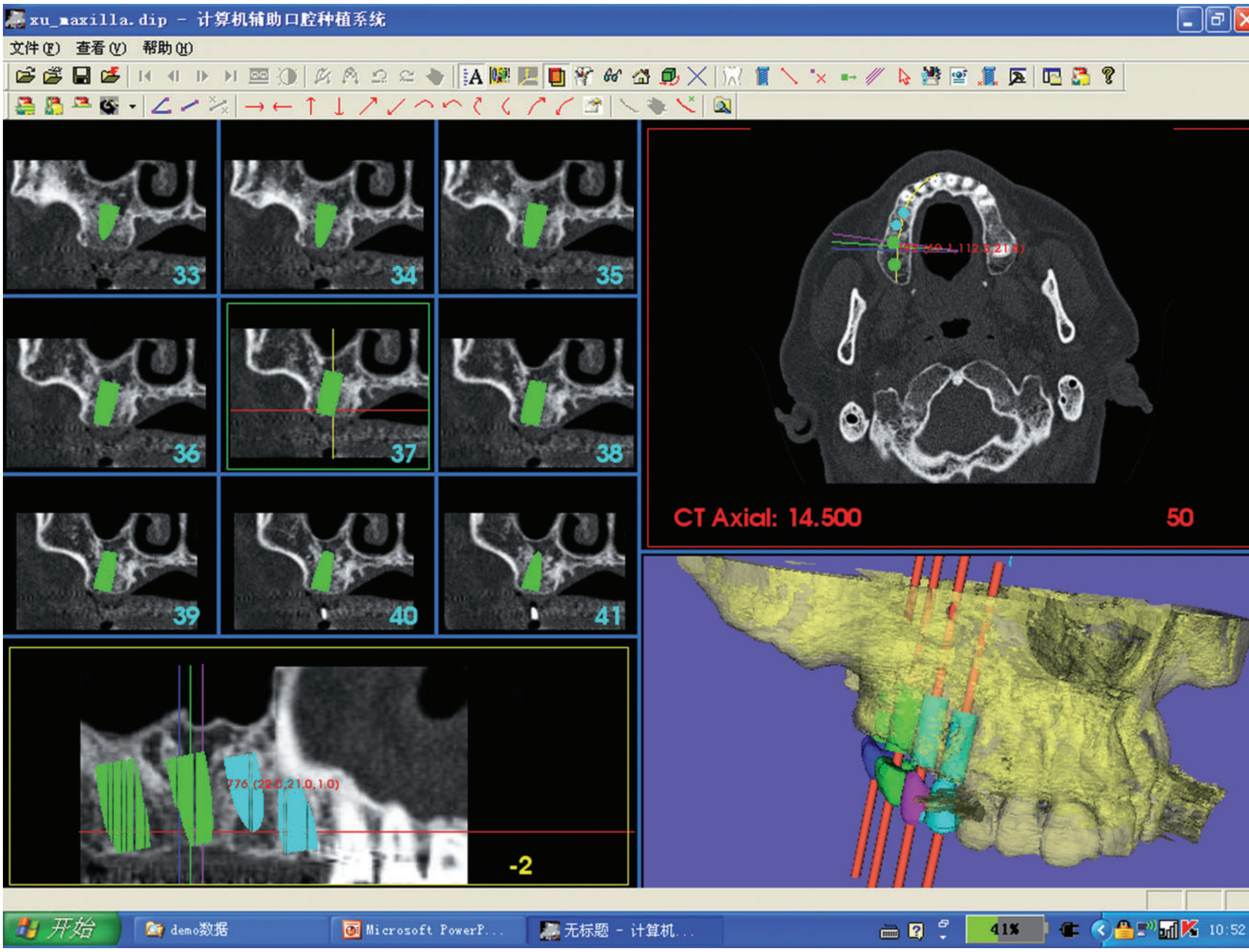

Figure 7 Preoperative surgical planning with the use of the Computer-Assisted Preoperative Planning for Oral Implant Surgery.

between the planned and the actual implants are shown in detail in Table 2 and illustrated in Figure 10.

As the precision of the implant placement depends largely on the ability to position the drill guide accurately on the underlying tissue, it is crucial to ensure the unique match between the templates and receptor sites. For bone-supported templates, because they were derived only from CT imaging, which was not as accurate as laser scanning (the resolution in x-, y-, z-axes of laser scanning usually reaches 0.05 mm; however, the relatively poor z-axis resolution of CT imaging is often lower than 0.5 mm), the match between the templates and the underlying bone ridge contour was not so perfect, and it also posed a significant challenge for prosthodontists to locate it at the optimal match position during the surgery. In addition, as an extensive flap is needed to be raised in the edentulous situations, the templates were not so stable because of the interference from the reflected flap.

In comparison, with regard to bone–tooth-combined-supported templates, the fixation was more stable because laser scanning technology enabled detailed dentition information, which brought about the unique topography between the match surface of the templates and the adjacent teeth. Furthermore, an extended flap was not needed for the exposure of the surgical site as the adjacent teeth played a significant role to support the template. Therefore, the precision of the osteotomies was improved. The presented data in Table 2 showed that the average distance deviations at the coronal and apical point of the implant were respectively 0.91 mm (range: 0.4–1.6) and 1.15 mm (range 0.4–1.7), and the average angle deviation was 2.31° (range: 0.9–3.6°) for bone-supported templates. However, these values were respectively reduced to 0.66 mm (range: 0.3–1.2), 0.86 mm (range: 0.4–1.2), and 1.84° (range: 0.6–2.8°) when the bone–tooth-combined-supported templates were used.

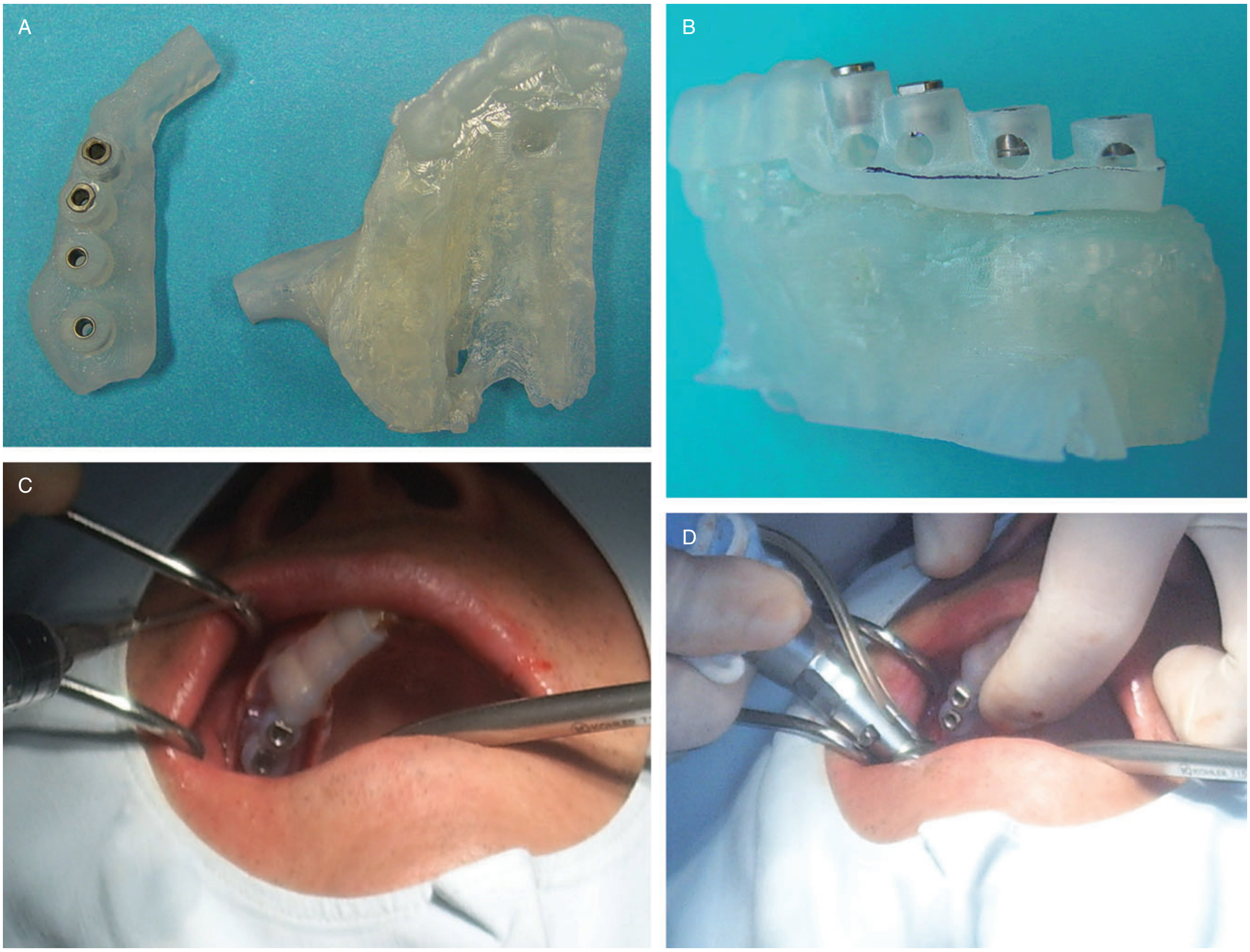

Figure 8 The application of the surgical template. *A*, The stereolithographic surgical template and maxillary phantom. *B*, Matching of the surgical template with the maxillary phantom. *C*, The template rested on the alveolar bone as well as the adjacent teeth. *D*, The application of the template during the surgery.

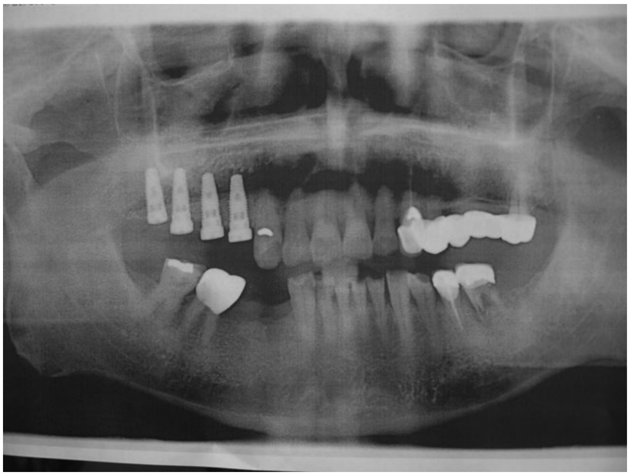

Figure 9 The postoperative panoramic radiographic image.

Nevertheless, whichever kinds of templates were employed, the presented data showed that the standard deviation was relatively high, and Figure 10 showed that the deviation increased in posterior regions. The reason lies in the relatively long drills, the thickness of the surgical guide, and the rather complicated surgical procedure in these regions. The poor visibility made it difficult for the surgeon to ensure complete depth of drilling and instrumentation especially in the posterior regions. Figure 10 also showed that the deviations at the coronal point were relatively larger than those at the apical point. These were because of the propagation of error, that is, a small initial error might result in relatively significant positional errors at the end of the osteotomy trajectory.

TABLE 2 Resulting Deviations

Implant No.	Distance Deviation (mm) at the Coronal Point	Distance Deviation (mm) at the Apical Point	Angle (°)
Patient 1			
1	1.6	1.7	3.6
2	0.8	1.4	2.3
3	0.9	0.9	1.9
4	0.4	0.7	1.9
Patient 2			
1	1.3	1.6	3.2
2	1.1	1.3	2.1
3	0.7	1.2	2.5
4	0.5	0.4	0.9
Mean	0.91	1.15	2.31
SD	0.41	0.45	0.83
Patient 3			
1	1.1	1.2	2.6
2	0.6	1.0	2.1
3	0.4	0.6	1.9
4	0.3	0.7	1.2
Patient 4			
1	1.2	1.0	2.8
2	0.8	1.1	1.8
3	0.6	0.9	1.7
4	0.3	0.4	0.6
Mean	0.66	0.86	1.84
SD	0.34	0.27	0.71

Note: implant no. 1: the second molar area; no. 2: the first molar area; no. 3: the second premolar area; no.4: the first premolar area.

However, as only two cases have been accomplished currently, this is a pilot study, and more clinical cases will be conducted to confirm the conclusions.

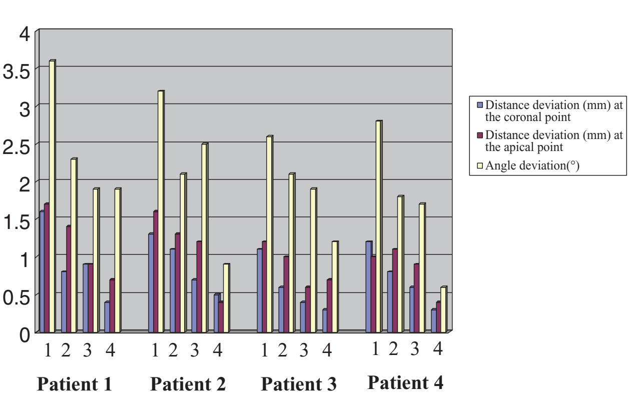

Figure 10 Resulting deviations.

DISCUSSION AND CONCLUSIONS

The complications caused by improper implant placement pose a significant challenge in implant dentistry.[3,4] CT-derived surgical templates enable clinically significant improvements in accuracy, time efficiency, and reduction in surgical error, benefiting the patient, surgeon, restorative dentist, and laboratory.[7] This leads to a higher predictability of the treatment outcome, and patients will have a better understanding of the implant prosthodontic treatment.

As a prerequisite for CT-derived surgical templates, preoperative planning software is explicitly discussed in this study, including its various functions and image processing algorithms. In order to fulfill the increasing requirements of oral implantology, a plug-in evolutive software architecture is introduced. By separating the preoperative planning software into several DLL divisions, we enhance modularity and flexibility in our system. It is really more accessible than rewriting the entire software in terms of adding new functionalities, including image processing algorithms, GUI, data management components, etc. Other advantages of using DLLs include reduced code footprint, lower memory utilization due to single-copy sharing, flexible development and testing, and functional isolation. As the current operating systems for the software is only based on Windows, our future work is to develop a cross-platform (Windows, Linux, and Mac Os X operating systems) application environment. With the introduction of DLL, this task can be easily accomplished as the only platform-dependent part of the library is the GUI.

To provide a link between the preoperative plan and the actual surgery, bone-, mucosa-, or tooth-supported templates are commercially available, for example, SurgiGuide® (Materialise, Leuven, Belgium), NobelGuide, etc. There are a few papers published on the accuracy of the transfer to the surgical field. Sarment and colleagues[12] performed cone beam CT scanning of epoxy edentulous mandibles and then used stereolithographic guides to perform osteotomies. They reported average deviations of 0.9 mm at the entrance and 1.0 mm at the apex between planned and actual locations. Di Giacomo and colleagues[14] used six surgical guides for four patients with 21 implants inserted, and they reported average deviations of 1.45 ± 1.42 mm and 2.99 ± 1.77 mm. Van Assche and colleagues[33] performed osteotomies for four cadavers and placed a total of 12 implants with stereolithographic guides based on cone beam CT imaging and the Procera® (Nobel Biocare AB, Göteborg, Sweden) software. They reported that placed implants (length: 10–15 mm) showed an average angular deviation of 2° (SD: 0.8, range: 0.7–4.0°) as compared with the planning, while the mean linear deviation was 1.1 mm (SD: 0.7 mm, range: 0.3–2.3 mm) at the entrance and 2.0 mm (SD: 0.7 mm, range: 0.7–2.4 mm) at the apex. Comparing the results presented above with the results achieved in this study, we concluded that the precision of the surgery was improved with the use of the novel bone–tooth-combined-supported surgical template. It is because of the fact this approach takes advantage of both laser scanning and CT imaging, which are complementary: the former is more accurate; however, it can only reflect the outer surface information of an object; the latter, vice versa. With detailed dentition information obtained from registration, the fixation of this kind of template is unique, stable, and reliable so that the accuracy of implant placement can be guaranteed.

Based on this principle, the same kind of mucosa–tooth-combined-supported template can also be fabricated. The advantage of mucosa–tooth-combined-supported template is that it allows flapless or minimally invasive surgery (MIS) with no incisions, no sutures, and very little bleeding. Currently, the trend of MIS becomes a mainstream in oral implantology because of optimal aesthetics with absence of scars produced by incisions and respect of papilla integrity.[21] From this perspective, the future of a combined-supported template is promising, and more clinical cases will be conducted to demonstrate its feasibility and reliability.

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REFERENCES

1. Askary AS, Meffert RM, Griffin T. Why do dental implants fail? Part I. Implant Dent 1999; 8:173–185.
2. Askary AS, Meffert RM, Griffin T. Why do dental implants fail? Part II. Implant Dent 1999; 8:265–277.
3. Lal K, White GS, Morea DN, Wright RF. Use of stereolithographic templates for surgical and prosthodontic implant planning and placement. Part I. The concept. J Prosthodont 2006; 15:51–58.
4. Lal K, White GS, Morea DN, Wright RF. Use of stereolithographic templates for surgical and prosthodontic implant planning and placement. Part II. A clinical report. J Prosthodont 2006; 15:117–122.
5. Reddy MS, Mayfield DT, Vanderven FJ, Jeffcoat MK. A comparison of the diagnostic advantages of panoramic radiography and computed tomography scanning for placement of root form dental implants. Clin Oral Implants Res 1994; 5:229–238.
6. Tardieu PB, Vrielinck L, Escolano E. Computer-assisted implant placement. A case report: treatment of the mandible. Int J Oral Maxillofac Implants 2003; 18:599–604.
7. Ganz SD. Presurgical planning with CT-derived fabrication of surgical guides. J Oral Maxillofac Surg 2005; 63:59–71.
8. Balshi SF, Wolfinger GJ, Balshi TJ. Surgical planning and prosthesis construction using computer tomography, CAD/

CAM technology, and the Internet for immediate loading of dental implants. J Esthetic Restor Dent 2006; 18:312–325.
9. Kupeyan HK, Shaffner M, Armstrong J. Definitive CAD/CAM-guided prosthesis for immediate loading of bone-grafted maxilla: a case report. Clin Implant Dent Relat Res 2006; 8:161–167.
10. Mischkowski RA, Zinser MJ, Neugebauer J, Kubler AC, Zoller JE. Comparison of static and dynamic computer-assisted guidance methods in implantology. Int J Comput Dent 2006; 9:23–35.
11. Jabero M, Sarment DP. Advanced surgical guidance technology: a review. Implant Dent 2006; 15:135–142.
12. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. Int J Oral Maxillofac Implants 2003; 18:571–577.
13. Sammartino G, Della Valle A, Marenzi G, et al. Stereolithography in oral implantology: a comparison of surgical guides. Implant Dent 2004; 13:133–139.
14. Di Giacomo GA, Cury PR, De Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. J Periodontol 2005; 76:503–507.
15. Wanschitz F, Birkfellner W, Watzinger F, et al. Evaluation of accuracy of computer-aided intraoperative positioning of endosseous oral implants in the edentulous mandible. Clin Oral Implants Res 2002; 13:59–64.
16. Wagner A, Wanschitz F, Birkfellner W, et al. Computer-aided placement of endosseous oral implants in patients after ablative tumour surgery: assessment of accuracy. Clin Oral Implants Res 2003; 14:340–348.
17. Brief J, Hassfeld S, Sonnenfeld U, et al. Computer-guided insertion of dental implants—a clinical evaluation. Int Congr Ser 2001; 1230:739–747.
18. Meyer U, Wiesmann HP, Runte C, et al. Evaluation of accuracy of insertion of dental implants and prosthetic treatment by computer-aided navigation in minipigs. Br J Oral Maxillofac Surg 2003; 41:102–108.
19. Brief J, Edinger D, Hassfeld S, Eggers G. Accuracy of image-guided implantology. Clin Oral Implants Res 2005; 16:495–501.
20. Randelzhofer P, De la Barrera JM, Spielberg M, Kurtz C, Strub JR. Three-dimensional navigation in oral implantology: a preliminary investigation. Int J Periodontics Restorative Dent 2001; 21:617–626.
21. Valente AF, Sbrenna BA, Buoni CC. CAD CAM drilling guides for transferring CT-based digital planning to flapless placement of oral implants in complex cases. Int J Comput Assist Radiol Surg 2006; 1:413–414.
22. Kreissl ME, Heydecke G, Metzger MC, Schoen R. Zygoma implant-supported prosthetic rehabilitation after partial maxillectomy using surgical navigation: a clinical report. J Prosthet Dent 2007; 97:121–128.
23. Lorensen WE, Cline HE. Marching cubes: a high resolution 3D surface construction algorithm. ACM Comput Graph 1987; 21:38–44.
24. Schroeder WJ, Zarge JA, Lorensen WE. Decimation of triangle meshes. Proc ACMM Siggraph 1992; 26:65–70.
25. Schroeder W, Martin K, Lorensen B. The Visualization Toolkit: an object-oriented approach to 3D graphics. New Jersey: Prentice Hall, 1997.
26. Lancaster JL, Eberly D, Alyassin A, Hunter DJ, Fox PT. A geometric model for measurement of surface distance, surface area, and volume from tomographic images. Med Phys 1992; 19:419–431.
27. Hughes SW, D'Arcy TJ, Maxwell DJ, et al. Application of a new discreet form of Gauss' theorem for measuring volume. Phys Med Biol 1996; 41:1809–1821.
28. Schutyser F, Swennen G, Suetens P. Robust visualization of the dental occlusion by a double scan procedure. Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv 2005; 8:368–374.
29. Roy A, Govil S, Miranda R. An algorithm to generate radial basis function (RBF)-like nets for classification problems. Neural Netw 1995; 8:179–201.
30. Arun KS, Huang TS, Blostein SD. Least-squares fitting of two 3-D point sets. IEEE Trans Pattern Anal Mach Intell 1987; 9:698–700.
31. Besl PJ, Mckay ND. A method for Registration of 3D shapes. IEEE Trans Pattern Anal Mach Intell 1992; 14:239–256.
32. Chivate PN, Puntambekar NV, Jablokow AG. Extending surfaces for reverse engineering solid model generation. Comput Ind 1999; 38:285–294.
33. Van Assche N, van Steenberghe D, Guerrero ME, et al. Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: a pilot study. J Clin Periodontol 2007; 34:816–821.