Use of a Surgical Navigation System for CT-Guided Template Production

Gerlig Widmann, MD[1]/Roland Widmann, CDT[2]/Ekkehard Widmann, MD, DDS[3]/Werner Jaschke, MD[4]/ Reto Bale, MD[5]

Purpose: *The purpose of this study was to evaluate in vitro the accuracy of 2 methods for computerized tomography (CT) -guided template production via a surgical navigation system.* ***Materials and Methods:*** *Oral implants were planned on CT scans of standard dental stone casts with integrated target pellets. Method 1 used the aiming device of the navigation system for direct positioning of 2-mm surgical bur tubes on the dental stone casts. In method 2, the aiming device was used to guide drillings into the dental stone casts, and the surgical bur tubes were indirectly positioned by metal rods inserted in the drill holes. In both methods the bur tubes were affixed in a resin template. The accuracy of the obtained templates was evaluated by postoperative CT scans using descriptive statistics and the Student* t *test (*$P < .05$ *considered significant).* ***Results:*** *The mean accuracy (normal deviation from the defined targets) of method 1 was 0.5 ± 0.3 mm (max 1.2 mm; n = 56). Mean accuracy for method 2 was 0.6 ± 0.3 mm (max 1.4 mm; n = 56). No significant difference was found between the maxillary and mandibular templates.* ***Discussion:*** *Conventional navigation systems already installed in many hospitals may be used for surgical template production. In contrast to intraoperative tool tracking, there is no need for patient tracking, and the planned implant axis can be rigidly secured as precisely as technically feasible with the help of an aiming device.* ***Conclusion:*** *Both methods of bur tube positioning may represent a precise means for CT-guided template production.* INT J ORAL MAXILLOFAC IMPLANTS 2007;22:72–78

Key words: *accuracy, image-guided template production, oral implant surgery, surgical navigation*

Computerized implant planning on 3-dimensional (3D) computerized tomographic (CT) data and image-guided surgery have been introduced recently to improve the accuracy of prosthodontic-driven implant positioning, minimize the risk of damaging vital anatomic structures, and allow full utilization of the available bone for maximum implant stability.[1–6] For image-guided implant positioning, 2 different approaches have been described: intraoperative navigation via surgical navigation systems[7–9] or use of CT-guided surgical templates.[5,10–14]

Surgical navigation systems enable real-time tracking of the bur according to the virtual plan on the CT data of the patient.[7–9] As a prerequisite for the navigation process, image-to-physical transformation (ie, registration) of the CT data (image) to the patient (physical) is required. It is usually based on a registration scan template that is supported with CT-recognizable reference elements such as ceramic spheres or a reference stone. In case of edentulous patients, invasively fixed bone markers are used. The individual registration template precisely fits to the remaining teeth and is held by the patient during the CT scan. To allow prosthodontic-driven oral implant planning on the CT data, the registration template integrates a radiopaque replica of the diag-

[1]Resident, Interdisciplinary Stereotactic Intervention and Planning Laboratory Innsbruck (SIP-Lab), Department of Radiology, Innsbruck Medical University, Austria.
[2]Dental Laboratory Czech, Absam, Austria.
[3]Private Practice, Zell/Ziller, Austria.
[4]Full Professor and Department Chairman, SIP-Lab, Department of Radiology, Innsbruck Medical University, Austria.
[5]Associate Professor and Head of SIP-Lab, Department of Radiology, Innsbruck Medical University, Austria.

Correspondence to: Dr Gerlig Widmann, Interdisciplinary Stereotactic Intervention and Planning Laboratory Innsbruck (SIP-Lab), Innsbruck Medical University, Department of Radiology, Clinical Division of Diagnostic Radiology I, Anichstrasse 35, A-6020 Innsbruck, Austria. Fax: +43 512 504 2758. E-mail: gerlig.widmann@i-med.ac.at

Fig 1 Modified Vogele-Bale-Hohner (VBH) mouthpiece (Medical Intelligence, Schwabmuenchen, Germany) and reference frame. *(Left)* The mouthpiece (A) was loaded with the dental impressions of the maxillary and mandibular casts, which were mounted to the dental articulator. *(Right)* The u-shaped registration frame included 7 spherical registration markers (glass, diameter 5.8 mm) broadly distributed around the region of interest and could be mounted to the anterior extensions of the mouthpiece.

nostic waxup or different radiopaque markers.[2,3,11,15,16] In the operating room, the registration template is again mounted on the patient but is additionally supported with tracking elements for the navigation system. Using optically-based tracking technology, these tracking elements consist of light-emitting diodes (LEDs) or passive reflecting elements for detection by the stereotactic camera of the navigation system. Position calculation is based on optical trigonometric measures of at least 3 tracking elements and requires a free line of sight between the tracking elements and the stereotactic camera. By recognition of the reference elements of the template, usually by indicating the markers with a probe of the navigation system, the software links the "virtual" markers on the CT data to the real markers in the operating room and allows transference of the virtual planning data to the surgical site. In addition, the tracking elements on the registration template provide intraoperative real-time tracking of the nonimmobilized patient. For navigation of the surgical tool, tracking elements are mounted to the toolholder. This enables the surgeon to guide the drill according to the planned path on the screen.

A second approach for intraoperative CT guidance is the manufacturing of surgical templates.[5,10–14] By means of a recognized registration template and a computerized transfer algorithm, mechanical positioners or special drilling machines are used to position surgical bur tubes on the patient's dental stone cast. The bur tubes are the affixed in the surgical template according to the CT plan. Alternatively, bone, mucosa, or tooth-supported surgical guides can be produced by stereolithographic rapid prototyping.

Many hospitals are already equipped with instrumentation for image-guided planning and interventions for use in various departments for different applications, eg, neurosurgery, spine surgery, tumor biopsy specimen removal, brachytherapy.[17,18] To use such systems for the additional application of image-guided implant positioning, a method for surgical template production has been created. The accuracy of surgical templates obtained via 2 different bur-tube positioning methods was evaluated in a model study.

MATERIALS AND METHODS

Model Fabrication

Eight standard dental stone casts (4 maxillae and 4 mandibles) were produced from volunteers and prepared with integrated targets (2-mm lead pellets) near the approximate apex of the hypothetical dental roots (one for each tooth, 14 lead pellets per cast). One hundred twelve individual nonidentical targets were obtained. The dental stone casts were mounted on a dental articulator (SAM Präzisionstechnik Munich, Germany; Fig 1).

Navigation System and Registration Technique

The Treon (Medtronic, Minneapolis, MN) is an optical-based navigation system. It consists of a transportable workstation, a stereotactic optical camera, a high-resolution display, a graphical user interface, and several software applications. For oral implant planning, the navigation system's Cranial-3 software was used.

The EasyTaxis aiming device (Philips Medical Systems, Best, The Netherlands) was used for adjustment of the surgical path along a predetermined linear trajectory to the target (Fig 2). Registration was based on a modified VBH mouthpiece and a registration frame (Medical Intelligence) supported with 7 spherical registration markers (glass, diameter 5.8 mm) broadly distributed around the region of interest (Fig 1). The mouthpiece was loaded with the dental impressions of the maxillary and mandibular casts in the dental articulator using dental impression material (CORRECT Vinyl Poly Siloxane; Jeneric/Pentron, Wallingford, CT). The reference frame could be mounted to the anterior extensions of the mouthpiece (Fig 2).

Fig 2 Laboratory setup for registration and navigation: A = base plate; B = mechanical arm for the fixation of the dental stone cast by the dental articulator's fixation system; C = EasyTaxis aiming device; D = reference arc. For registration, the mouthpiece with the registration frame attached was mounted to the fixed dental stone cast. By touching the registration markers with the navigation probe, the "virtual" (CT-data) markers were linked to the corresponding "real" (setup) markers, which allowed the transfer of the 3D surgical plan to the dental stone cast.

Imaging and 3D Surgical Planning

Multislice spiral CT scanning of the maxillary and mandibular stone casts with the individual mouthpiece and reference frame was performed in the Light Speed QX/I (GE Medical Systems, Waukesha, WI) with a slice thickness of 1.25 mm (120 kV, 80 mA, gantry 0 degrees, rotation time 0.8 second, reconstruction interval 0.6 mm, bone plus algorithm). Via the hospital's intranet the standardized (DICOM) CT data was transferred to the workstation of the navigation system.

Oral implants were planned on the reformatted CT data of the dental stone casts with the entry at the centers of the dental crowns and the target points at the center of the corresponding lead pellets.

Laboratory Setup

The laboratory setup consisted of the navigation system, a base plate (40 × 30 cm, with multiple fixing areas for mechanical arms), and 3 adjustable mechanical arms to hold the aiming device, the dental stone cast, and a reference arc (Fig 2). The dental stone casts were held in place by the fixation system of the dental articulator. The reference arc is part of the navigation system and corrects for movements of the base plate with respect to the stereotactic camera.

Registration and Navigation

The first step of registration was indication of the center of the markers of the registration frame on the reformatted CT data. On the laboratory setup, the mouthpiece with the attached registration frame was mounted to the fixed dental cast. By touching the 7 registration markers with the navigation probe, the "virtual" (CT data) markers were linked to the corresponding "real" (setup) markers. The root-mean-square-error (RMSE) between the registration markers was used as an indicator of the registration accuracy; it was only accepted if it was less than 0.5 mm. In addition, the registration accuracy was independently checked by touching landmarks on the cast and comparing the real position to the virtual position on the screen. After registration, the mouthpiece and the external registration frame were removed. The reference arc maintained a constant relationship to the dental cast; thus, it was not necessary to attach a reference arc to the model itself.

To translate the 3D plan into the positioning of bur tubes for the production of surgical templates, the EasyTaxis aiming device was adjusted under the guidance of the navigation system. The position was locked when the calculated deviation to the planned path was less than 0.5 mm and 1 degree, as indicated by the software of the navigation system.

Method 1 (Direct Bur Tube Positioning)

In method 1, surgical bur tubes 2 mm long were positioned on the dental stone casts by a metal rod advanced through the adjusted aiming device (Fig 3). One by one, the bur tubes were then polymerized into a prefabricated resin template (Orthocryl template resin; Dentaurum J. P. Winkelstroeter KG, Ispringen, Germany) using an ultraviolet (UV) light-curing resin (Versyo; Heraeuskulzer, Hanau, Germany) and a UV light source (Optilux/Demetron; Kerr Dental, Orange, CA). Two maxillary and 2 mandibular surgical templates each containing 14 bur tubes with the dimension of the pilot drill of a standard surgical drill set were fabricated. For evaluation, drillings were performed through the obtained templates.

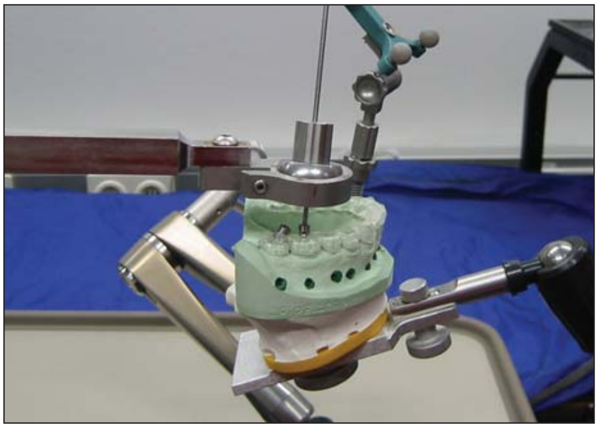

Fig 3 Method 1 (direct bur tube positioning). *(Left)* The aiming device of the navigation system was used for direct positioning of 2-mm surgical bur tubes on the dental stone casts. One by one, the bur tubes were affixed into a prefabricated template with blue light-curing resin. *(Right)* Finished surgical template on one of the mandibular casts.

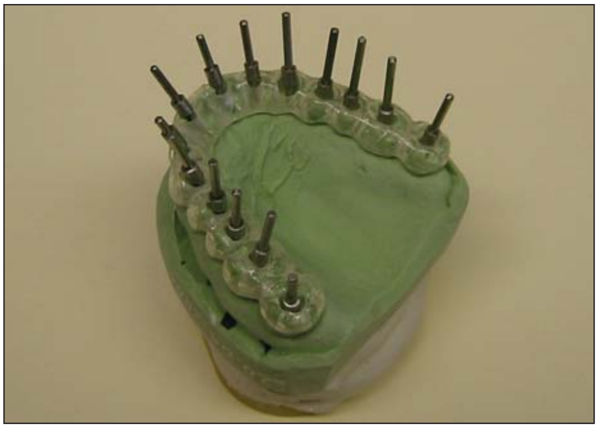

Fig 4 Method 2 (indirect bur tube positioning). *(Left)* The aiming device of the navigation system was used to guide 2-mm drillings into the dental stone casts, and the surgical bur tubes were indirectly positioned by metal rods inserted in the drill holes. The bur tubes were affixed in the surgical template in a single session in the dental laboratory. *(Right)* Finished surgical template on a duplicate maxillary cast.

Method 2 (Indirect Bur Tube Positioning)

In method 2, the aiming device was used to guide 2 mm drillings into the casts. Metal rods were inserted into the drill holes. Surgical bur tubes were positioned using the metal rods and fixed into a resin template in a single session in the dental laboratory (Orthocryl template resin; Dentaurum J. P. Winkelstroeter KG; Fig 4). Two maxillary and 2 mandibular templates were fabricated (2-mm bur tubes, 14 per template).

For evaluation, drillings were performed through the templates on duplicate sets of the initial dental stone casts because, in contrast to method 1, the initial casts had already been drilled. The duplicate casts were generated with the help of a silicone duplication form (Dublisil 15; Dreve-Dentamid, Unna, Germany).

Evaluation

All drilled dental casts were scanned following the described protocol. The CT datasets were sent to the navigation system. On the "postoperative" CT scans, the accuracy was defined as the normal deviation of the achieved drilling from the planned target. A path with its entry point in the center of the proximal drill hole and the target point in the center of the distal drill hole was determined and virtually elongated to the plane of the center of the lead balls. The normal distance by which the drill would have passed the target was evaluated.

To evaluate the drilled duplicate casts for method 2, the postoperative CT data was linked to the CT data of the planning model (with the integrated target points) via paired point-matching using the markers on the registration frame.

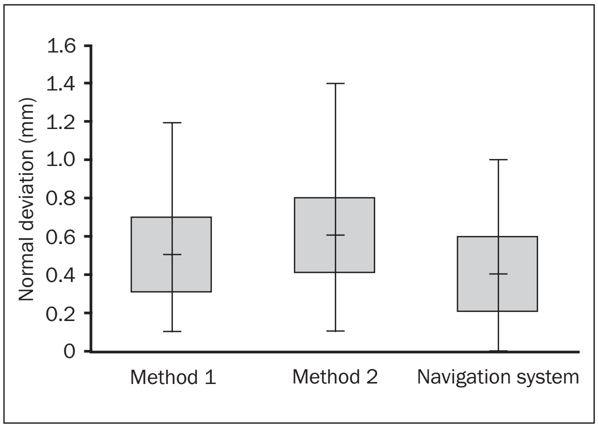

Fig 5 Box plots showing median, quartile, and extreme values of target-based normal deviations in mm for the obtained surgical templates made by the direct and the indirect techniques (methods 1 and 2, respectively) and for the drillings guided by the aiming device of the navigation system.

Table 1 Accuracy (Normal Deviation in mm) of the Template-Guided Drillings

	Method 1 (n = 56)	Method 2 (n = 56)	Navigation system* (n = 56)
Mean	0.5	0.6	0.4
SD	0.3	0.3	0.3
Minimum	0.1	0.1	0.0
Maximum	1.2	1.4	1.0

*Accuracy of the drillings guided by the aiming device of the navigation system.

Descriptive statistical analysis was used. Normal distribution was tested by the Kolmogorov-Smirnov test, and *t* tests were performed to determine whether there were significant differences between the maxillary and mandibular templates. Duration and effort were evaluated for both methods.

RESULTS

The mean accuracy for method 1 was 0.5 ± 0.3 mm (n = 56), and the maximum deviation was 1.2 mm. The mean accuracy for method 2 was 0.6 ± 0.3 mm (n = 56), with a maximum deviation of 1.4 mm. The mean accuracy of the navigated drillings guided by the aiming device, which was the initial step for template manufacturing by method 2, was 0.4 ± 0.3 mm (n = 56), with a maximum deviation of 1 mm (Table 1, Fig 5).

The accuracy of the required image fusion for evaluation of method 2 was 0.1 mm RMSE, as indicated by the matching software of the navigation system.

All measures showed normal distribution ($P > .05$), and there were no statistical outliers. No significant difference was found between the accuracy of the maxillary and the mandibular templates for either method ($P > .05$).

The registration procedure was completed in approximately 10 minutes. Navigated adjustment of the aiming device required 2 to 3 minutes per implant. With method 1, about 30 minutes was needed for the fabrication of the resin template, and approximately 5 minutes was required for the subsequent fixation of 1 surgical bur tube. Method 2 required less effort and allowed for faster completion in a single session, with an average duration of 35 minutes per template.

DISCUSSION

In implant-supported oral restoration, state-of-the-art treatment combines both functional and esthetic concepts. The diagnostic waxup of the prosthodontic reconstruction preferentially guides the positioning of the proposed implants, and customized surgical templates are used for guidance of the implant positioning during surgery.[15,16,19,20] However, conventional 2-dimensional imaging, such as dental panoramic tomography and plain film tomography, is sensitive to expansion and distortion factors and possible projection errors, depending on patient positioning, which can lead to misinterpretation of bone height. Most importantly, it does not provide information about the bucco-oral dimension.[2,20,21] Conventional surgical templates provide some orientation and angulation guidance, but only CT-guided templates are fabricated based on precise knowledge of the radiographic 3D anatomy of the patient.[5,10–14]

To overcome the aforementioned limitations of existing methods, computer-aided implant planning based on 3D CT data and surgical realization using navigation systems or image-guided templates have been introduced.[2,4,5,8–10] For in vitro application of surgical navigation, Wanschitz and associates[22] found mean accuracies at the tip of the implant of 1.36 mm measured from the lingual cortex and 1.44 mm measured from the buccal cortex, with a maximum deviation of 3.5 mm (n = 20). Similar results were found for bur tracking guided by head-mounted displays.[23]

Using a mechanical positioning device–based template fabrication technique, Besimo and associates[4] reported mean accuracies of 0.6 mm for the maxilla (n = 26) and 0.3 mm for the mandible (n = 51), with a maximum deviation of 1.5 mm. With rapid prototyping templates, Sarment and colleagues[24] found an accuracy of 1.0 mm at the tip of the implant (maximum 1.6 mm; n = 25), which corresponds with the results of van Steenberghe and coworkers,[11] who observed a mean accuracy of 0.9 mm.

Compared to bur tracking, template-based techniques seem to show a higher accuracy at the tip of the implant. The in vitro studies cited show differences of about half a millimeter in mean value and approximately 2 mm with respect to maximum deviation. As angular deviation increases along depth, surgical templates with fixed drill guidance may provide an advantage over bur tracking. The latter method may be susceptible to hand tremor and perception inaccuracies of about 0.25 mm and 0.5 degrees,[25] in addition to a navigation system's spatial navigation error of about 0.3 to 0.4 mm.[26] To improve the application performance, bur tracking companies are currently working on intelligent drill speed control, which would slow down the drill speed when the position and angle of the bur stand outside a certain degree of accuracy or immediately stop the drill before it reached a vital anatomic structure.

In this study a multipurpose navigation system was adapted for image-guided template production using 2 different bur tube positioning methods. Considering that duplicate dental stone casts were used for evaluation of method 2 and that there was an image fusion error of approximately 0.1 mm, similar accuracy was demonstrated with the 2 methods. The 2 methods were slightly less accurate (0.1 to 0.2 mm) as compared to navigated drillings through the aiming device. Both techniques used the same registration and navigation techniques. However, method 2 required less effort than method 1 and allowed for faster consecutive template manufacturing. Using method 2, creation of the surgical template could be finished in a single session in a dental laboratory.

Registration and navigation for the procedures described were simple and did not differ substantially from other image-guided applications of the navigation system (eg, radiofrequency ablation of liver and bone tumors, retrograde drilling of osteochondral talar lesions, thermo-coagulation of the gasserian ganglion, otorhinolaryngeal surgery, neurosurgery). Standard dental stone casts were used without modifications, and the fixation system of the dental articulator was included for fast and simple cast fixation.

In previous CT-guided techniques, radiopaque scanning splints for visualization of the diagnostic waxup of the prosthodontic reconstruction on the CT scan were fundamental prerequisites for oral implant planning. In the presented technique such scanning splints were not necessary, because in the laboratory setup the waxup could be indicated by the pointer of the navigation system.

In contrast to intraoperative tool tracking, navigation is executed in the laboratory, and there is no need for patient tracking. The planned implant axis can be rigidly secured as precisely as technically feasible with the help of an aiming device. During surgery, surgical templates provide stable drilling performance independent of the surgeon's ability to convert navigational data.

In the presented study, accuracy was defined as the deviation of the drilled path from the given target (the tip of the planned implant), which has a strong clinical value because it refers to the experienced accuracy from the viewpoint of the executing surgeon. The accuracy of the introduction of the drill was not included in this measuring method. The depth of the drilling can be controlled by depth gauges or by a mechanical stop on the drill at a precise distance from the top of the bone (or the top of the bur tube).

The precise transfer of virtual planning to the surgical site largely depends on the accuracy and reproducibility of the registration procedure.[6,13,22,26] In marker-based registration, the slice thickness should be as small as possible, and the markers should be as large as possible (sufficiently larger than a voxel) to be clearly estimated on the CT scan.[27] In this study, spiral CT scanning was performed with a slice thickness of 1.25 mm, which was the smallest possible with the CT scanner used. The diameter of the registration markers on the registration frame was 5.8 mm, which was well beyond the slice thickness. Thus, it may not be possible to increase accuracy substantially by reducing the slice thickness.

Computer assistance has the potential to combine optimal oral implant planning, precise and reproducible surgery, transparency, and forensic documentation of every step. General acceptance of this technique is increasing.[9,14] With similar multipurpose tools (base plate, mechanical arms, aiming device), the presented principle may be realized with other commercial navigation systems. With the cooperation of interdisciplinary planning and template fabrication centers, neither the oral surgeon nor the laboratory technician need to purchase the necessary hard- or software, which may keep down additional treatment costs while improving the standard (non–image-guided) procedure.

CONCLUSION

A multipurpose navigation system was successfully adapted for surgical template production. Similar accuracy was found for direct and indirect methods of bur tube positioning. No significant differences were found between maxillary and mandibular templates. Method 2 (indirect method) allowed for faster template manufacturing and required less effort than method 1. Consistent with previous literature,[4,5,10–14,24] the presented study indicates that surgical templates represent a precise means to translate 3D oral implant planning.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the radiation technicians of the Clinical Division of Radiology I who were involved with this research, especially Thomas Lang, Martin Knoflach, and Christoph Hinterleithner from the SIP Lab.

Disclosure: Prof Bale is a coinventor of the Vogele-Bale-Hohner (VBH) mouthpiece, the external registration frame, and the aiming device, and a coshareholder in its financial returns.

REFERENCES

1. Dula K, Mini R, van der Stelt P, Buser D. The radiographic assessment of implant patients: Decision-making criteria. Int J Oral Maxillofac Implants 2001;16:80–89.
2. Jacobs R. Preoperative radiologic planning of implants in compromised patients. Periodontol 2000 2003;33:12–25.
3. Kopp KC, Koslow AH, Abdo OS. Predictable implant placement with a diagnostic/surgical template and advanced radiographic imaging. J Prosthet Dent 2003;89:611–615.
4. Besimo CE, Lambrecht JT, Guindy JS. Accuracy of implant treatment planning utilizing template-guided reformatted computed tomography. Dentomaxillofac Radiol 2000;29(1):46–51.
5. Vrielinck L, Politis C, Schepers S, Pauwels M, Naert I. Image-based planning and clinical validation of zygoma and pterygoid implant placement in patients with severe bone atrophy using customized drill guides. Preliminary results from a prospective clinical follow-up study. Int J Oral Maxillofac Surg 2003;32:7–14.
6. Gaggl A, Schultes G, Kaercher H. Navigational precision of drilling tools preventing damage to the mandibular canal. J Craniomaxillofac Surg 2001;29:271–275.
7. Watzinger F, Birkfeller W, Wanschitz F, et al. Positioning of dental implants using computer-aided navigation and an optical tracking system: Case report and presentation of a new method. J Craniomaxillofac Surg 1999;27:77–81.
8. Sießegger M, Schneider B, Mischowski RA, et al. Use of image-guided navigation system in dental implant surgery in anatomically complex operation sites. J Craniomaxillofac Surg 2001;29:276–281.
9. Ewers R, Schicho K, Truppe M, et al. Computer-aided navigation in dental implantology: 7 years of clinical experience. J Oral Maxillofac Surg 2004;62:329–334.
10. 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.
11. van Steenberghe D, Naert I, Andersson M, Brajnovic I, Van Cleynenbreugel J, Suetens P. A custom template and definitive prosthesis allowing immediate implant loading in the maxilla: A clinical report. Int J Oral Maxillofac Implants 2002;17:663–670.
12. van Steenberghe D, Malevez C, van Cleynenbreugel J, et al. Accuracy of drilling guides for transfer from three-dimensional CT-based planning to placement of zygoma implants in human cadavers. Clin Oral Implants Res 2003;14:131–136.
13. Fortin T, Champleboux G, Bianchi S, Buatois H, Coudert JL. Precision of transfer of preoperative planning for oral implants based on cone-beam CT-scan images through a robotic drilling machine. Clin Oral Implants Res 2002;13:651–656.
14. Fortin T, Bosson JL, Coudert JL, Isidori M. Reliability of preoperative planning of an image-guided system for oral implant placement based on 3-dimensional images: An in vivo study. Int J Oral Maxillofac Implants 2003;18:886–893.
15. Becker CM, Kaiser DA. Surgical guide for dental implant placement. J Prosthet Dent 2000;83:248–251.
16. Almog DM, Torrado E, Meitner SW. Fabrication of imaging and surgical guides for dental implants. J Prosthet Dent 2001;85:504–508.
17. Bale RJ, Burtscher J, Eisner W, et al. Computer-assisted neurosurgery by using a noninvasive vacuum-affixed dental cast that acts as a reference base: Another step toward a unified approach in the treatment of brain tumors. J Neurosurg 2000;93:208–213.
18. Bale RJ, Freysinger W, Gunkel AR, et al. Head and neck tumors: Fractionated frameless stereotactic interstitial brachytherapy-initial experience. Radiology 2000;214:591–595.
19. Wat PY, Chow TW, Luk HW, Comfort MB. Precision surgical template for implant placement: a new systematic approach. Clin Implant Dent Relat 2002;4(2):88–92.
20. Iplikcioglu H, Akca K, Cehreli MC. The use of computerized tomography for diagnosis and treatment planning in implant dentistry. J Oral Implantol 2002;28(1):29–36.
21. BouSerhal C, Jacobs R, Quirynen M, van Steenberghe D. Imaging technique selection for the preoperative planning of oral implants: A review of the literature. Clin Implant Dent Relat Res 2002;4(3):156–172.
22. 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(1):59–64.
23. Wanschitz F, Birkfellner W, Figl M, et al. Computer-enhanced stereoscopic vision in a head-mounted display for oral implant surgery. Clin Oral Implants Res 2002;13:610–616.
24. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. Int J Oral Maxillofac Implants 2003;18:571–577.
25. Schermeier O, Hildebrand D, Lueth T, Hein A, Szymansky D, Bier J. Accuracy of an image-guided system for oral implantology. In: Lemke HU, Vannier MW, Inamura K, Farman AG (eds). International Congress Series: Elsevier Science, 2001;1230:748–752.
26. Casap N, Wexler A, Persky N, Schneider A, Lustmann J. Navigation surgery for dental implants: Assessment of accuracy of the Image Guided Implantology System. J Oral Maxillofac Surg 2004;(suppl 2);62:116–119.
27. Maurer CR, Fitzpatrick JM, Wang MY, Galloway RL, Maciunas RJ, Allen GS. Registration of head volume images using implantable fiducial markers. IEEE Trans Med Imaging 1997;16:447–462.