Three-Dimensional Accuracy of Guided Implant Placement: Indirect Assessment of Clinical Outcomes

Susanne Platzer, DDS;* Georg Bertha, MD, DDS;[†] Alexander Heschl, DMS, DDS;[‡]
Walther A. Wegscheider, MD, PHD, DDS;[§] Martin Lorenzoni, MD, PHD, DDS[¶]

ABSTRACT

Purpose: Precise preoperative implant planning and its exact intraoperative transfer are crucial for successful implant-supported rehabilitation of partially or completely edentulous patients. In the present pilot study, optical laser scanning was used to evaluate deviations between three-dimensonal computer-assisted planned and actual implant positions by indirect methods.

Material and Methods: Five patients receiving a total of 15 implants were included in this study. The used planning software was SimPlant 12.0 (Materialise Dental, Leuven, Belgium) to visualize the implant positions, and with an appropriate guided surgery protocol (Navigator™, Biomet 3i, Palm Beach Gardens, FL, USA) implant positions were implemented via tooth-supported stereolithografic surgical guides. All implants (Osseotite™, Biomet 3i) were inserted in a flapless approach and immediately provided with prefabricated temporary splinted restorations. Intraoral pickup impressions were taken postoperatively, and the implant positions of the master casts were compared with presurgical casts. Implant replica deviations were evaluated by three-dimensional optical laser scanning providing distances and angulations between implant replicas.

Results: Overall, the postsurgical implant replica positions were found to deviate from the positions in the preoperative cast by a mean of 0.46 ± 0.21 mm (range: 0.09–0.85 mm). Positional deviations were 0.27 ± 0.19 mm (range: 0.04–0.60 mm) along the x-axis representing the buccal-lingual directions, 0.15 ± 0.13 mm (range: 0.0–0.34 mm) along the y-axis representing the ventrodorsal direction, and 0.28 ± 0.19 mm (range: 0.02–0.59 mm) along the z-axis representing cranial and apical directions. Rotational deviations amounted to 14.04 ± 11.6° (range: 0.09–36.47°).

Conclusions: The results of this pilot study demonstrate precise transfer of implant replica position by means of simulated guided implant insertion into a preoperative cast and a postoperative cast obtained from impressioning. Further studies are needed to identify appropriate evaluation techniques and mechanisms to increase the transfer precision of three-dimensional planning and guiding systems.

KEY WORDS: accuracy, dental implants, guided implant surgery, immediate provisionalization, laser scan

*Research associate, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Graz, Austria; [†]Former resident, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Graz, Austria; [‡]Research associate, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Graz, Austria; [§]Professor and chairman, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Graz, Austria; [¶]Professor, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Graz, Austria

Reprint requests: Univ. Prof. Dr. Martin Lorenzoni, Department of Prosthodontics, School of Dentistry, Medical University of Graz, Auenbruggerplatz 12, 8036 Graz, Austria; e-mail: martin.lorenzoni@medunigraz.at

Disclaimer: This study was completely financed by department funding. The authors state that they have no financial interest in any company or any of the products mentioned in this article.

DOI 10.1111/j.1708-8208.2011.00406.x

INTRODUCTION

Implant-supported rehabilitation is established today as a predictable approach to restore the masticatory system in terms of function and esthetics.[1–3] The clinical steps involved are determined by existing morphological conditions pertaining to bone quantity and quality, sensitive anatomical structures, and the objective to achieve ideal three-dimensional implant positions driven by restorative considerations.

Conventional panoramic radiography can only yield two-dimensional information about the planned implant site. This kind of examination does not offer insight into the three-dimensional morphology of implant sites. Therefore, conventional orthopantomograms are an inadequate diagnostic tool, even though they involve less radiation exposure for patients.[4–7] Computed tomography (CT) and cone beam CT (CBCT) allow for three-dimensional visualization of bone and nearby anatomical structures without superimposition, and they also allow conclusions to be drawn about bone quality in the prospective implant region.[8–11] Based on Digital Imaging and Communications in Medicine (DICOM) records of presurgical CT or CBCT scans with an incorporated radiopaque scanning template, three-dimensional reconstruction of surgical sites can be obtained for implant planning driven by restorative considerations.

Accurate surgical implementation of the restorative treatment plan is another essential requirement over and above the planning as such. The transfer accuracy of various three-dimensional navigation systems has been evaluated in a number of studies.[12–15] The accuracy of image-guided surgery has been defined as the "deviation in location or angle of the plan compared with the result," including "all possible single errors from image acquisition to surgical implant positioning," which are "cumulative and interactive."[16] Sources of error may be related both to technical procedures like fabrication of the template and to the properties associated with specific materials.[17] However, factors that may contribute to transfer inaccuracies in guided implant surgery are manifold and have been poorly evaluated.

Previous studies evaluating the transfer precision of guided surgery have usually required a postsurgical CT scan for three-dimensional verification of the implant positions. Considering that this extra radiation exposure is barely acceptable, the present study introduced a laser-scanning technique to verify the transfer precision between implant replica position in a preoperative cast obtained by guided implant insertion through the surgical template, utilized for prefabrication of provisional restorations, and the surgically implemented implant positions, represented by replica position in a postoperative cast obtained from impressioning.

MATERIALS AND METHODS

Figure 1 illustrates the design of this clinical pilot study. The study was conducted following the International Conference on Harmonisation for Good Clinical Practice Guidelines for Clinical Trials and the Declaration of Helsinki as revised in 2000. Institutional approval was obtained from the local ethics commission.

Patients

Five patients (mean age: 45.2 years) with intermediate gaps in the posterior mandible were included in the study. All gave their informed consent after being comprehensively informed about the study and all were treaded at the University Dental Clinic Graz, Austria. A total of 15 implants were inserted using a flapless approach. The distribution of implants is shown in Table 1.

Each patient's medical history, periodontal status (using a modified Community Periodontal Index of Treatment Needs [CPITN] periodontal status[18]), and functional status (using the Graz dysfunction index[19]) were obtained during the screening examination. An alginate impression of the surgical site was taken to fabricate a study cast using type IV dental stone (Shera Hardrock, Shera, Lemförde, Germany). All prosthetic restorations were planned by an experienced restorative dentist using a restoration-driven approach. A radiopaque scan prosthesis was fabricated using a self-curing resin (Paladur, Heraeus Kulzer, Hanau, Germany) mixed with barium-sulfate powder in a 3:1 ratio.

Radiographic Examination

All patients were examined by diagnostic radiography via an orthopantomogram (Orthophos XG Plus, Sirona, Bensheim, Germany) during the screening visit. A Somatom Sensation 16 unit (Siemens, Bensheim, Germany) was employed for all CT scans pertaining to the study (settings: collimation: 16×0.75 mm; layer thickness: 0.75 mm; increment: 0.5 mm; 12 kV; 80 mAs; field of view: 105 cm; rotation time: 0.75 second; kernel: H60 sharp).

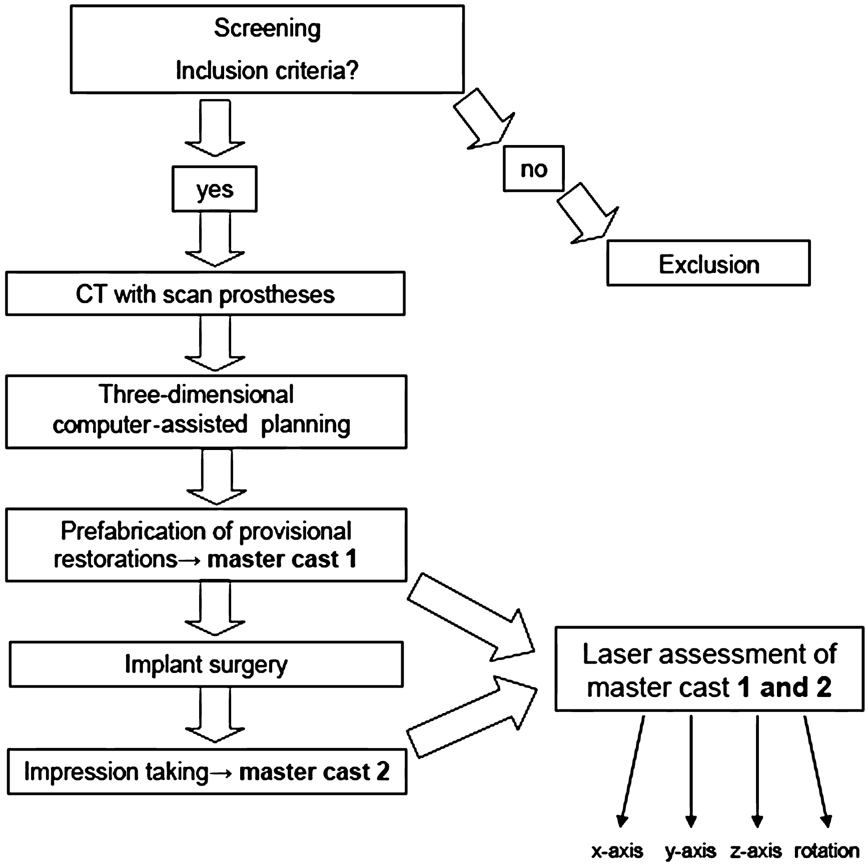

Figure 1 Illustration of treatment flow.

Three-Dimensional Planning

Computer-assisted planning was performed by a well-qualified investigator under standardized conditions, based on the predefined restorative plan visualized through the radiopaque scan template. Appropriate planning software (Simplant®12.0, Materialise Dental, Leuven, Belgium) was used on a Microsoft Windows (XP Professional, Service Pack 3) platform in conjunction with a Pentium dual-core computer (E6700@ 3.20 GHz, 3.19 GHz, 3.46 GB Random Access Memory [RAM], Intel® 4 Series Express Chipset 1024 MB, Intel® GMA 4500, Figure 2). The DICOM records thus generated were transmitted online to the fabrication center to create the surgical guides by stereolithography, as shown in Figure 3. To ensure a precise fit of these tooth-supported templates, a stone cast of each patient was shipped to the manufacturer for matching with the virtual planning, allowing any inaccuracies to be corrected directly on the cast.

Simulated Implant Surgery on Casts

The surgical template was used in conjunction with the proprietary laboratory kit (Navigator® Laboratory Kit, Biomet 3i, Palm Beach Gardens, FL, USA) to transfer the

TABLE 1 Distribution of Implants

Region	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Third quadrant	36	36		35	35
	37	37		36	36
					37
Fourth quadrant		46	46		44
		47	47		45

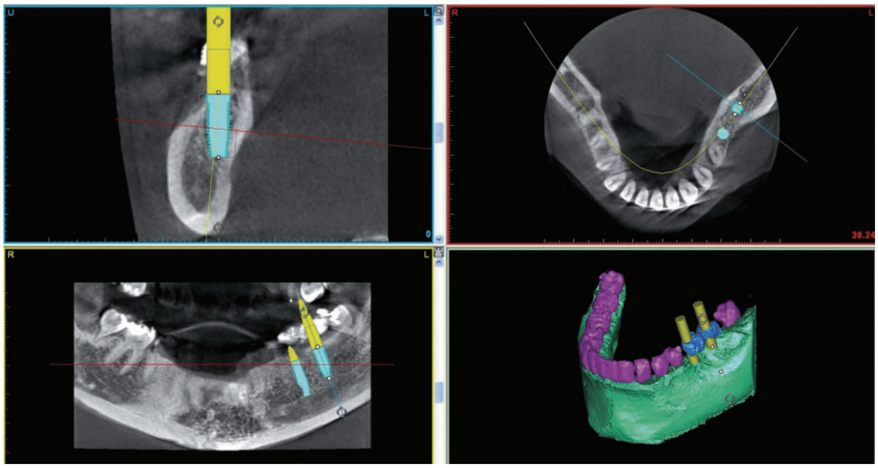

Figure 2 Three-dimensional computer-assisted backward planning.

data of three-dimensional implant position to the cast. Laboratory analogues were inserted into the stone cast in accordance with the planned positions and fixed with plaster, taking care to achieve correct position of the internal hex connection. Prefabricated temporary splinted acrylic resin crowns (SR Ivocron®, Ivoclar Vivadent, Schaan, Liechtenstein) on temporary abutments (Provide®, Biomet 3i) were manufactured based on the preoperative master cast thus obtained (hereafter cast 1; Figure 4).

Guided Implant Placement

All patients were instructed to rinse with chlorhexidine digluconate (0.2%). The surgical procedures were conducted under local anesthesia (Ultracain dental forte®, Sanofis-Aventis, Vienna, Austria). All patients received antibiotics 1 day before surgery for 5 days.

Implants were inserted in a flapless approach through the surgical guides based on a drilling protocol that was enclosed with the navigator guide (Biomet 3i) (Figure 5). Primary stability exceeded 45 Ncm in all cases. The final position of each implant was achieved via a groove in the master sleeve and a marking on the implant mount. To reflect the true implant positions achieved by surgery, a pickup impression was taken with an open custom tray (SR Ivolen® Tray Material, Ivoclar Vivadent) and appropriate transfer copings (GingiHue® Post, Biomet 3i) using a polyether impression material (Impregum™ Penta Soft™, 3 M ESPE, Neuss, Germany). After removing the impression, prefabricated temporary restorations were immediately delivered with temporary cement (TempBond®, Kerr, GmbH, Karlsruhe, Germany) to temporary abutments

Figure 3 Stereolithographic template located on the cast for prefabrication of the temporary restoration.

Figure 4 Prefabricated temporary splinted restoration.

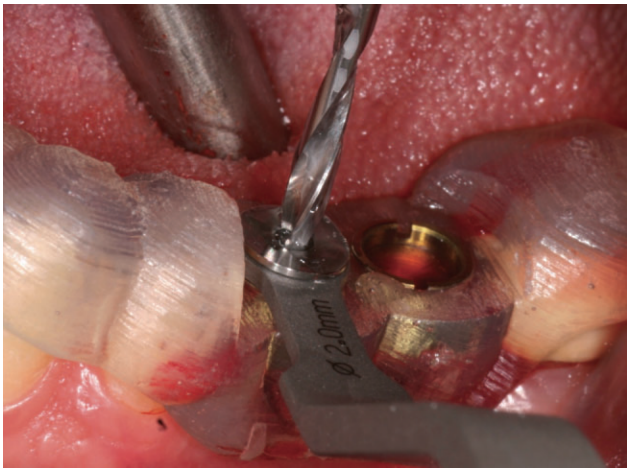

Figure 5 Flapless implant surgery following the drilling protocol.

(Provide®, Biomet 3i), as seen in Figure 6. Care was taken to prevent any centric and eccentric occlusal contacts of the splinted temporary restorations. Follow-up examinations focusing on occlusion and hygiene were performed at 4-week intervals. Any manipulations other than recementing mobile restorations were avoided.

After a predefined recovery time for the impression material, another master cast (hereafter cast 2) was fabricated in type IV dental stone (Shera Hardrock, Shera) using laboratory analogues (Biomet 3i) that were connected to the transfer copings (Biomet 3i) representing the actual implant positions achieved during surgery. This postoperative cast 2 was fabricated by a dental technician without the use of a soft tissue substitute.

Figure 6 Incorporated resin-made, splinted, prefabricated restorations immediately after surgery.

Measurement Techniques

Two casts were thus available for each patient; cast 1 representing the implant positions anticipated by three-dimensional planning, while cast 2 reflected the positions that had actually been implemented during implant surgery (indirect method). An optical scanner (Laserscan 3D, Willytech, Feldkirchen-Westerham, Germany) was used on both casts for three-dimensional evaluation of the implant positions (Figure 7). To transfer the three-dimensional information from implant level to abutment level, sandblasted (Cobra Al_2O_3, Renfert, Hilzingen, Germany) healing abutments (Encode®, Biomet 3i) with an antirotational mechanism were attached to the implants with an insertion torque of 25 Ncm. Based on clearly reproducible features of the occlusal relief displayed by the neighboring teeth, the various scanning strips were matched to form a three-dimensional model. Positional (three-dimensional) and rotational deviations were identified by recording the internal hex connection based on the notches milled into the Encode® (Biomet 3i) healing abutment. Positional deviations are represented in the frontal

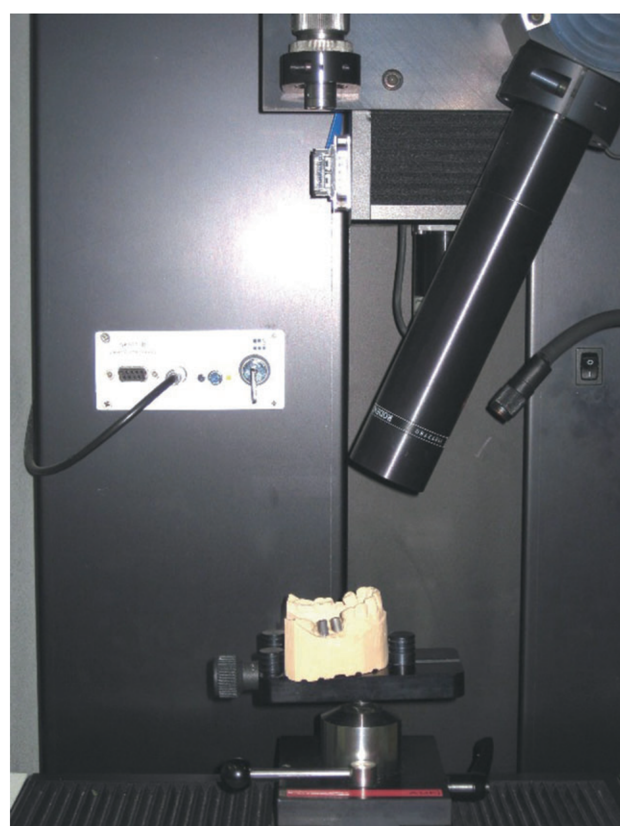

Figure 7 Laser scan procedure.

(buccolingual, x-axis), sagittal (ventrodorsal, y-axis), and vertical (apico-crestal, z-axis) planes.

RESULTS

A total of 15 implants were placed to rehabilitate intermediate gaps in the posterior mandible of five patients. An overview is provided in Table 1. Implant treatment covered both mandibular quadrants in two of these patients and one quadrant in three patients. None of the implants were lost during the observation period. One implant (site 36 in patient 4) had to be overruled manually on being found to lack primary stability during surgery. This implant was excluded from analysis but is included in Table 1 for completeness. Overall, the postsurgical replica positions on cast 2 were found to deviate from the replica positions on cast 1 by a mean of 0.46 ± 0.21 mm (range: 0.09–0.85 mm).

Positional Deviations

As these parameters were evaluated based on a system of coordinates, the deviations measured in different directions within the various quadrants are indicated by positive and negative values. Values along the *x-axis* indicate buccolingual deviations along the frontal transversal axis (frontal plane). Positive and negative values were obtained to the right and left, respectively, which had different implications in the left and right posterior segments. In the third quadrant, positive values indicate buccal deviations to the right, whereas negative values indicate lingual deviations to the left. In the fourth quadrant, positive values indicate lingual deviations to the right, whereas negative values indicate buccal deviations to the left. The mean deviation measured along the x-axis was 0.27 ± 0.19 mm (range: 0.04–0.60 mm). Both directions (buccal and lingual) are included in this value, and 33% of all deviations were observed in buccal directions (Figure 8).

Values along the *y-axis* indicate ventrodorsal deviations along the sagittal transversal axis. Positive and negative values were obtained toward the ventral and dorsal, respectively. The mean deviation measured along the y-axis was 0.15 ± 0.13 mm (range: 0.0–0.34 mm). Of these deviations, 27% were observed in ventral directions (Figure 9).

Values along the *z-axis* indicate cranio-apical deviations along the frontal sagittal axis. Positive and negative values were obtained toward the cranial and apical, respectively. The mean deviation measured along the z-axis was 0.28 ± 0.19 mm (range: 0.02–0.59 mm). Of these deviations, 27% were observed in cranial directions as shown in Figure 10.

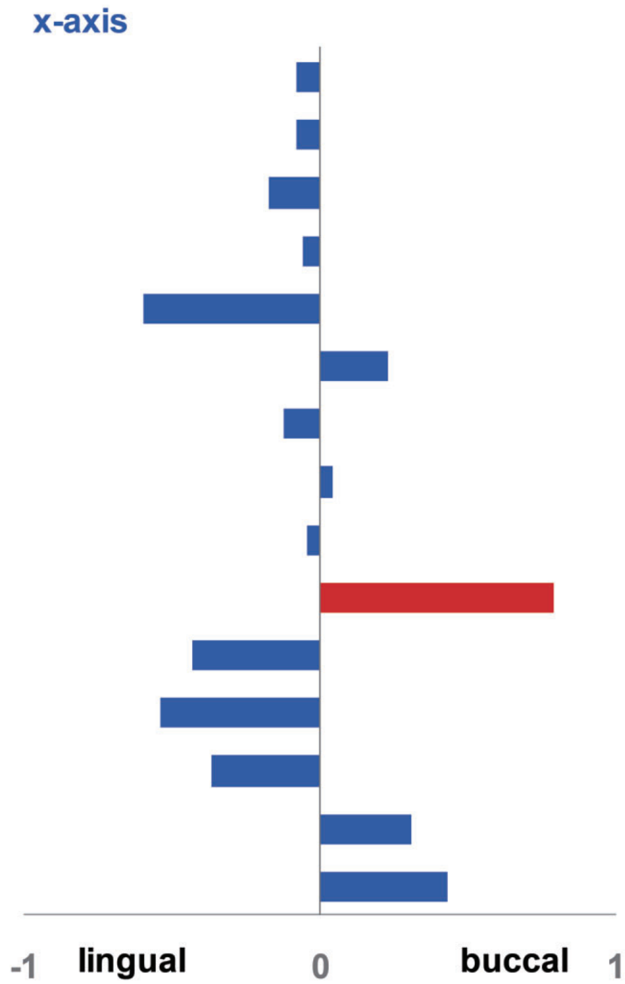

Figure 8 Deviations in the x-axis distributed to the buccolingual aspect.

Rotational Deviations

Changes in rotation were evaluated based on the position of the antirotational mechanism and internal hex connection. Negative and positive values indicate rotational deviations to the left (counterclockwise) and right (clockwise), respectively. A mean rotational deviation of 14.04 ± 11.6° (range: 0.09–36.47°) was obtained. The largest deviation observed in this series was 36.47° (patient 1).

A boxplot analysis of the measured deviations in the x-, y-, and z-axes, as well as of the total displacement, is shown in Figure 11.

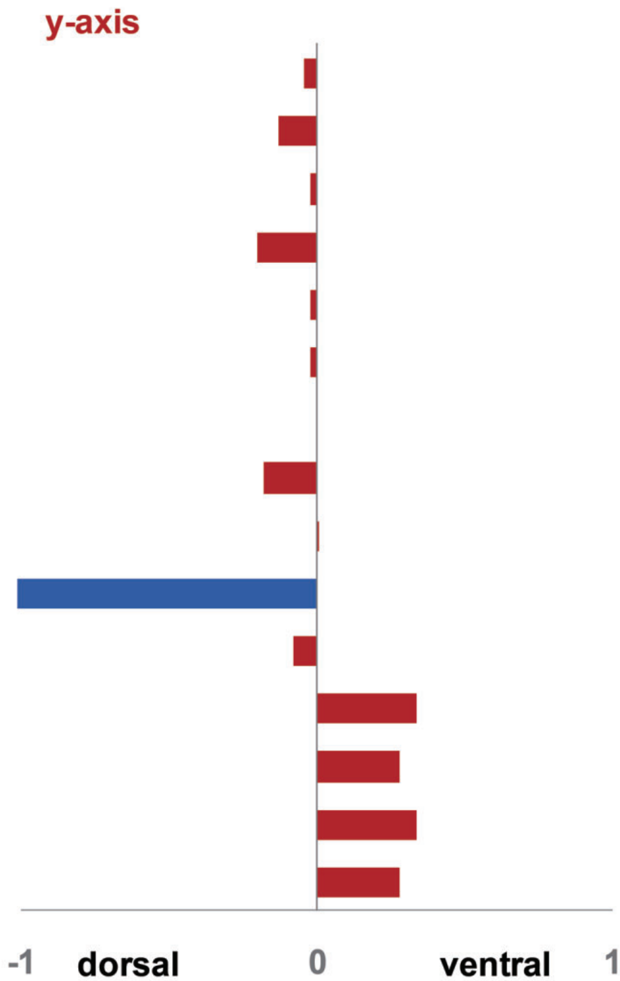

Figure 9 Deviations in the y-axis distributed to the ventrodorsal aspect.

DISCUSSION

Essential requirements for esthetic and functional success of implant treatment include precise assessment of the initial situation, custom planning of the restorative treatment, and accurate surgical implementation of the treatment plan. Several authors (Brief and colleagues,[20] Hoffmann and colleagues,[21] and Sarment and colleagues[22]) have pointed out that significantly better precision is obtained with computer-assisted systems than with strictly freehand approaches to implant insertion. Three-dimensional computer-assisted implant planning, transferred to surgery via stereolithographic drilling templates, facilitates complex therapeutic approaches like flapless implant placement or insertion of prefabricated temporary restorations.[23–26] The success of these concepts, however, depends on the precision of surgical implementation.

Transfer precision of computer-assisted three-dimensional planning systems has been evaluated and controversially discussed in the literature. Study designs have ranged from phantom studies performed on resin models[20,27,28] through cadaveric studies[14,29,30] up to in vivo investigations.[15,31,32] Also, the measurement techniques used in these studies have been diverse and difficult to compare. Eggers and colleagues and Hoffmann and colleagues[27,28] used a three-dimensional digitizer arm for three-dimensional measurement of deviations, whereas Brief and colleagues[20] employed a coordinate-measuring machine. Vasak and colleagues,[15] Di Giacomo and colleagues,[31] and Van Assche and colleagues[33] utilized data from DICOM records that had been generated by CT scans obtained before and after implant placement to evaluate the transfer precision of template-guided implant placement. This strategy allowed positional deviations to be assessed even in the apical

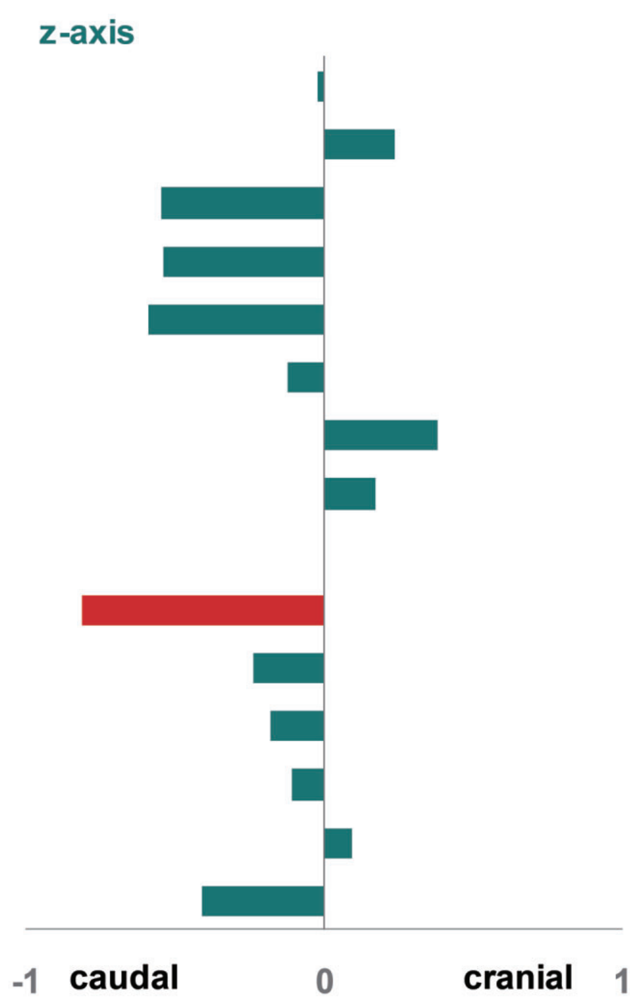

Figure 10 Deviations in the z-axis distributed to the craniocaudal aspect.

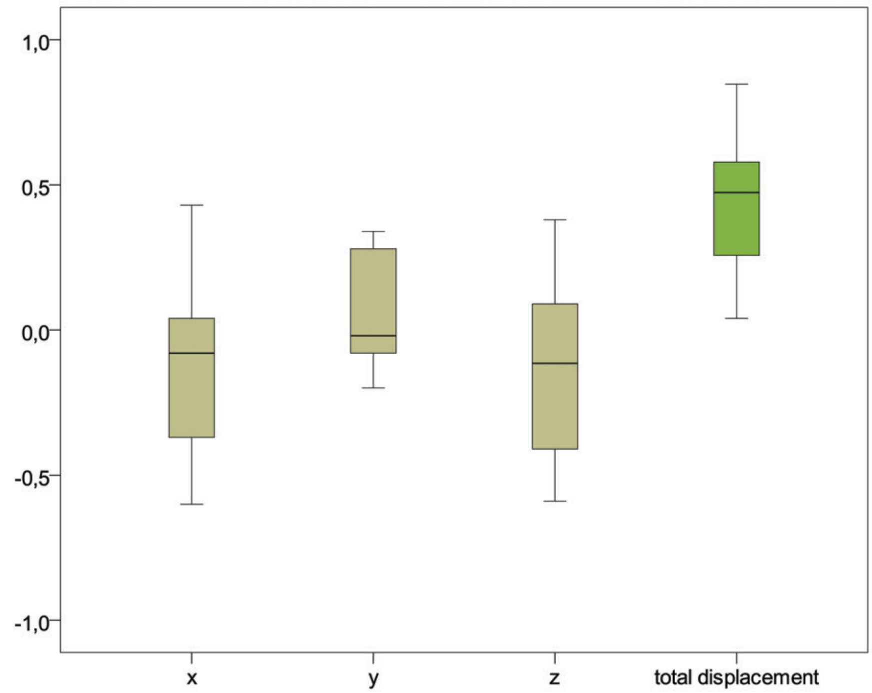

Figure 11 Boxplot analysis of measured deviations in the x-, y-, and z-axes and the total displacement.

region. While laser scanning, as applied in the present study, does not offer insight into three-dimensional changes at apical implant levels, this technique will not expose patients to additional radiation. Brief and colleagues[20] pointed out that such additional exposure was a disadvantage. The laser-scan technique presented in this pilot study should therefore be considered a useful alternative to techniques based purely on superimposition of CT records, although only transfer precision of implant replica position achieved through stereolithographic-template-guided positioning from different cast situations is actually measured.

To transfer the measured deviations into the clinical situation, an additional production error of the stereolithographic template of ±0.1 mm[34] and a deviation of 0.14 mm resulting from a glue gap between the resin tube and the metal guiding cylinder (company-specific value, Materialise Dental NV, Leuven, Belgium) have to be added up to the results achieved in the present study.

Vasak and colleagues[15] reported positional deviations at the implant shoulder of 0.37/0.35/0.31 mm along the x/y/z-axis in a sample of partially edentulous jaws. They pointed out that all values they measured remained within the safety zone predefined by the planning software (total deviations based on all indications: 1.42/1.50/1.85 mm along the x/y/z-axis). Respecting this safety margin to sensitive anatomical structures (e.g., alveolar inferior nerve, neighboring teeth, and maxillary sinus) will eliminate the risk of injury-related postsurgical complications even if inaccuracies within the reported range are present. Even with an additional production error, the results of the present study were within the company's recommended safety margin of 1.5 mm around the planned implant and 2 mm around sensitive structures.

A phantom study by Eggers and colleagues[27] yielded a mean positional deviation of 0.45 ± 0.04 mm (range: 0.14–0.91 mm) at the implant shoulder. These deviations, too, fall within the safety zone and are very close to the overall mean deviation of 0.46 ± 0.21 mm (range: 0.09–0.85 mm) obtained in the present study. Van Assche and colleagues[33] reported a mean positional deviation of 0.6 ± 0.3 mm at the hex connection of TiUnite implants (Nobel Biocare, Zürich, Switzerland). Komiyama and colleagues[35] introduced an "experimental model matching approach," which was also based on optical scanning, and obtained a total mean deviation at the implant hex connections of 0.39 mm (range: 0.06–0.97) in the mandible. The mean positional deviations obtained in the present study at the implant shoulder (0.27/0.15/0.28 mm along the x/y/z-axis) were slightly lower compared with the findings reported by Vasak and colleagues,[15] Di Ciacomo and colleagues,[31] or Van Assche and colleagues[33] but were close to the findings of Komiyama and colleagues.[35]

The precision in transferring the data of implant replica position from cast 1 (representing planned situation, used for prefabrication of provisional restoration) to cast 2 (representing surgical implemented position, obtained by impressioning) can be attributed to the exclusive use of tooth-supported drill guides offering accurate and stable intraoral anchorage. Vasak and colleagues,[15] by contrast, used a range of dissimilar guides for different indications. Di Giacomo and colleagues[31] used multiple guides even within one patient by selecting different designs based on drill diameters, expressly attributing the deviations they observed to this switching of guides between drilling steps. Van Assche and colleagues[33] also concluded that intraoperative stability of guides was highly relevant for transfer precision. A tendency toward greater positional deviations must be expected in cadaveric studies[14] due to tooth mobility and resilience of the mucosa resulting from the fixation process.

However, intraoral stabilization of the surgical guides is not the only factor influencing the precision of transferring planning data to surgery. Vasak and colleagues[15] noticed learning effects in their study that were operator dependent, with one of two surgeons getting more precise in the buccolingual plane while the other achieved increasingly better results in the corono-apical plane. In our study, we found no indications for any specific learning curves. Implant planning had to be overruled in one case because of poor primary stability, which led to exclusion from statistical analysis while the implant affected continues to be listed for completeness.

Immediate loading protocols are known to depend heavily on primary stability for success.[32,36–38] Both Ottoni and colleagues[37] and Esposito and colleagues[32] found the implant success rates of immediately restored implants to correlate with primary stability, although the effect of occlusal contacts on clinical success remains unclear. Ottoni and colleagues[37] investigated a sample of 23 immediately loaded implants, all exhibiting an insertion torque of <20 Ncm. Given an implant success rate of only 56.5%, the authors concluded that immediate loading should be confined to implants achieving an insertion torque of ≥32 Ncm. A systematic review by Esposito and colleagues[32] produced evidence that immediate loading offered better chances of success than early loading. Moreover, combining immediate loading with flapless surgery will not only reduce chair time but has also been reported to involve less pain and postsurgical discomfort.[25] Immediate loading with prefabricated temporary restorations after guided implant surgery eliminates the need for impression taking with manipulation of the implant directly after the procedure. Temporary abutments and crowns play an important role especially in the anterior maxilla because they allow conditioning of the peri-implant soft tissue (in the presence of adequate primary stability) for enhanced esthetic outcomes.[39]

If all safety margins recommended by the manufacturer are respected, any deviations that clinically may occur will remain within the safety zone, thus effectively minimizing the risk of encroaching on sensitive anatomical structures. All the deviations currently documented in the literature and obtained by our study group do not have any adverse effects other than perhaps reducing the precision of fit of the superstructures involved. Some caution should therefore be exercised with regard to creating prefabricated temporary restorations, although all of them could be inserted without requiring significant adjustments in the present study. Immediate delivery of final restorations that will offer no or reduced possibilities of subsequent adjustment cannot be recommended as a predictable approach based on the currently available data.

Attention should be paid to the limitations imposed on the present outcomes resulting from the introduced measuring technique. Because of abandonment of matching two CT data sets (pre- and postoperatively), the results of the present measuring technique reflect transfer precision of implant replicas from a preoperative cast to a postoperative cast.

Various sources of error that may lead to inaccuracies in guided implant surgery are considered to play an important role. Widmann and Bale[16] and Pettersson and colleagues[40] pointed out that CT slice thickness, movements by patients, and scan parameter settings[41] are major modifiers of accuracy during image acquisition. A mean recording accuracy of 0.68 mm has been reported.[16] A comparison between CBCT and multislice CT for segmentation accuracy based on a phantom model revealed a range of 4.2 to 1.0 mm.[42] We therefore used standardized parameters in our radiographic CT examinations to eliminate systematic error from our study. Other modifiers of precision include fabrication of the template[16] (reported by van Steenberghe and colleagues[43] to involve a typical error of 0.1–0.2 mm) and mechanical error caused by the gap between the guiding cylinder and the bur.[44] Human error remains an uncontrollable factor throughout all steps involved in guided implant placement and three-dimensional planning. However, the total sum of potential errors during each step has not been fully evaluated.[45]

Consequently, there is a need to identify appropriate evaluation techniques and mechanisms capable of optimizing transfer precision and eliminating errors of three-dimensional planning and guiding systems.

CONCLUSIONS

The results of this pilot study demonstrate precise transfer of implant replica position by means of simulated guided implant insertion into a preoperative cast and a postoperative cast obtained from impressioning. Further studies are needed to identify appropriate evaluation techniques and mechanisms to increase the transfer precision of three-dimensional planning and guiding systems.

REFERENCES

1. Aglietta M, Siciliano VI, Zwahlen M, et al. A systematic review of the survival and complication rates of implant supported fixed dental prostheses with cantilever extensions after an observation period of at least 5 years. Clin Oral Implants Res 2009; 20:441–451.
2. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008; 19:119–130.
3. Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clin Oral Implants Res 2004; 15:667–676.
4. Garg AK, Vicari A. Radiographic modalities for diagnosis and treatment planning in implant dentistry. Implant Soc 1995; 5:7–11.
5. Lam EW, Ruprecht A, Yang J. Comparison of two-dimensional orthoradially reformatted computed tomography and panoramic radiography for dental implant treatment planning. J Prosthet Dent 1995; 74:42–46.
6. Sakakura CE, Morais JA, Loffredo LC, Scaf G. A survey of radiographic prescription in dental implant assessment. Dentomaxillofac Radiol 2003; 32:397–400.
7. White SC, Heslop EW, Hollender LG, Mosier KM, Ruprecht A, Shrout MK. Parameters of radiologic care: an official report of the american academy of oral and maxillofacial radiology. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2001; 91:498–511.
8. Aranyarachkul P, Caruso J, Gantes B, et al. Bone density assessments of dental implant sites: 2. Quantitative cone-beam computerized tomography. Int J Oral Maxillofac Implants 2005; 20:416–424.
9. Bolin A, Eliasson S, von Beetzen M, Jansson L. Radiographic evaluation of mandibular posterior implant sites: correlation between panoramic and tomographic determinations. Clin Oral Implants Res 1996; 7:354–359.
10. Gray CF, Redpath TW, Bainton R, Smith FW. Magnetic resonance imaging assessment of a sinus lift operation using reoxidised cellulose (Surgicel) as graft material. Clin Oral Implants Res 2001; 12:526–530.
11. Gahleitner A, Podesser B, Schick S, Watzek G, Imhof H. Dental CT and orthodontic implants: imaging technique and assessment of available bone volume in the hard palate. Eur J Radiol 2004; 7:257–262.
12. Horwitz J, Zuabi O, Machtei EE. Accuracy of a computerized tomography-guided template-assisted implant placement system: an in vitro study. Clin Oral Implants Res 2009; 20:1156–1162.
13. Schneider D, Marquardt P, Zwahlen M, Jung RE. A systematic review on the accuracy and the clinical outcome of computer-guided template-based implant dentistry. Clin Oral Implants Res 2009; 20 (Suppl 4):73–86.
14. 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.
15. Vasak C, Watzak G, Gahleitner A, Strbac G, Schemper M, Zechner W. Computed tomography-based evaluation of template (NobelGuide(™))-guided implant positions: a prospective radiological study. Clin Oral Implants Res 2011; 22:1157–1163.
16. Widmann G, Bale RJ. Accuracy in computer-aided implant surgery – a review. Int J Oral Maxillofac Implants 2006; 21:305–313.
17. D'haese J, Van De Velde T, Komiyama A, Hultin M, De Bruyn H. Accuracy and complications using computer-designed stereolithographic surgical guides for oral rehabilitation by means of dental implants: a review of the literature. Clin Implant Dent Relat Res 2010; May 11. DOI: 10.1111/j.1708-8208.2010.00275.x. [Epub ahead of print].
18. Ainamo J, Ainamo A. Partial indices as indicators of the severity and prevalence of periodontal disease. Int Dent J 1985; 35:322–326.
19. Riegler H, Haas M. Der grazer dysfunktionsindex – eine methode zur einschätzung des funktionszustandes im stomatognathen system. Stomatologie 1995; 92:371–383.

20. Brief J, Edinger D, Hassfeld S, Eggers G. Accuracy of image-guided implantology. Clin Oral Implants Res 2005; 16:495–501.
21. Hoffmann J, Westendorff C, Gomez-Roman G, Reinert S. Accuracy of navigation-guided socket drilling before implant installation compared to the conventional free-hand method in a synthetic edentulous lower jaw model. Clin Oral Implants Res 2005; 16:609–614.
22. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. Int J Oral Maxillofac Implants 2003; 18:571–577.
23. Arisan V, Karabuda CZ, Ozdemir T. Implant surgery using bone- and mucosa-supported stereolithographic guides in totally edentulous jaws: surgical and post-operative outcomes of computer-aided vs. standard techniques. Clin Oral Implants Res 2010; 21:980–988.
24. Casap N, Laviv A, Wexler A. Computerized navigation for immediate loading of dental implants with a prefabricated metal frame: a feasibility study. J Oral Maxillofac Surg 2011; 69:512–519.
25. Fortin T, Bosson JL, Isidori M, Blanchet E. Effect of flapless surgery on pain experienced in implant placement using an image-guided system. Int J Oral Maxillofac Implants 2006; 21:298–304.
26. Gillot L, Noharet R, Cannas B. Guided surgery and presurgical prosthesis: preliminary results of 33 fully edentulous maxillae treated in accordance with the nobelguide protocol. Clin Implant Dent Relat Res 2010; 12 (Suppl 1):e104–e113.
27. Eggers G, Patellis E, Muhling J. Accuracy of template-based dental implant placement. Int J Oral Maxillofac Implants 2009; 24:447–454.
28. Hoffmann J, Westendorff C, Schneider M, Reinert S. Accuracy assessment of image-guided implant surgery: an experimental study. Int J Oral Maxillofac Implants 2005; 20:382–386.
29. Ruppin J, Popovic A, Strauss M, Spuntrup E, Steiner A, Stoll C. Evaluation of the accuracy of three different computer-aided surgery systems in dental implantology: optical tracking vs. stereolithographic splint systems. Clin Oral Implants Res 2008; 19:709–716.
30. 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.
31. 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.
32. Esposito M, Grusovin MG, Felice P, Karatzopoulos G, Worthington HV, Coulthard P. Interventions for replacing missing teeth: different times for loading dental implants. Cochrane Database Syst Rev 2009; (1):CD003878.
33. Van Assche N, van Steenberghe D, Quirynen M, Jacobs R. Accuracy assessment of computer-assisted flapless implant placement in partial edentulism. J Clin Periodontol 2010; 37:398–403.
34. Petzold R, Zeilhofer HF, Kalender WA. Rapid prototyping technology in medicine – basics and applications. Comput Med Imaging Graph 1999; 23:277–284.
35. Komiyama A, Pettersson A, Hultin M, Näsström K, Klinge B. Virtually planned and template-guided implant surgery: an experimental model matching approach. Clin Oral Implants Res 2011; 22:308–313.
36. Javed F, Romanos GE. The role of primary stability for successful immediate loading of dental implants. A literature review. J Dent 2010; 38:612–620.
37. Ottoni JM, Oliveira ZF, Mansini R, Cabral AM. Correlation between placement torque and survival of single-tooth implants. Int J Oral Maxillofac Implants 2005; 20:769–776.
38. Romanos GE. Surgical and prosthetic concepts for predictable immediate loading of oral implants. J Calif Dent Assoc 2004; 32:991–1001.
39. De Rouck T, Collys K, Wyn I, Cosyn J. Instant provisionalization of immediate single-tooth implants is essential to optimize esthetic treatment outcome. Clin Oral Implants Res 2009; 20:566–570.
40. Pettersson A, Komiyama A, Hultin M, Näsström K, Klinge B. Accuracy of virtually planned and template guided implant surgery on edentate patients. Clin Implant Dent Relat Res 2010; May 11. DOI: 10.1111/j.1708-8208.2010.00285.x. [Epub ahead of print].
41. Stumpel LJ. Deformation of stereolithographically produced surgical guides: an observational case series report. Clin Implant Dent Relat Res 2010; Feb 11. DOI: 10.1111/j.1708-8208.2010.00268.x. [Epub ahead of print].
42. Loubele M, Jacobs R, Maes F, et al. Image quality vs radiation dose of four cone beam computed tomography scanners. Dentomaxillofac Radiol 2008; 37:309–318.
43. 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.
44. Cassetta M, Giansanti M, Di Mambro A, Calasso S, Barbato E. Accuracy of two stereolithographic surgical templates: a retrospective study. Clin Implant Dent Relat Res 2011; Jul 11. DOI: 10.1111/j.1708-8208.2011.00369.x. [Epub ahead of print].
45. Komiyama A, Hultin M, Näsström K, Benchimol D, Klinge B. Soft tissue conditions and marginal bone changes around immediately loaded implants inserted in edentate jaws following computer guided treatment planning and flapless surgery: a >/=1-year clinical follow-up study. Clin Implant Dent Relat Res 2009; Sep 29. DOI: 10.1111/j.1708-8208.2009.00243.x. [Epub ahead of print].