Deviations between Placed and Planned Implant Positions: An Accuracy Pilot Study of Skeletally Supported Stereolithographic Surgical Templates

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ABSTRACT

Purpose: The aim of the present study was to evaluate deviations between virtually planned and placed implants by the use of skeletally supported stereolithographic templates.

Materials and Methods: Ten consecutive patients were selected for virtual three-dimensional implant planning using the Facilitate™ software (Astra Tech AB, Mölndal, Sweden). Computer tomography images were obtained in the pre- and postoperative phase. Four deviation parameters (i.e. global, angular, depth, and lateral deviation) were defined and calculated between the planned and the placed implants, using the coordinates of their respective apical and coronal points.

Results: Deviations at the coronal positions appeared to be smaller (95% confidence interval: 0.15–1.0) as compared with apical positions (95% confidence interval: 0.14–1.1). But only the difference with regard to lateral measurements appeared to be statistically significant ($p = .03$). Except for depth ($p = .01$), no significant association between mesial or more distal locations could be detected concerning global ($p = .07$), lateral ($p = .87$), and angular ($p = .56$) values in mixed model analyses. Overall, there was a slight tendency for higher values for more distal locations.

Conclusion: As slight deviations between planned and placed implants especially may occur even with skeletal-supported templates, the clinician should be aware not to overestimate advocated surgical safety by using static navigation tools.

KEY WORDS: computer tomography, computer-guided implant dentistry, software planning, stereolithography, surgical guide

INTRODUCTION

To improve surgical accuracy and intraoperative safety of dental implantation, state-of-the-art treatment regimes aim at an advanced implementation of favorable features of computer-assisted planning and navigation into the clinical environment.[1,2] In spite of obvious advantages of computer-based three-dimensional (3D) visualization and image-guided navigation, high operating costs, financial expenditure, prolonged preoperative time requirement, and demanding knowledge of technical issues reveal these technologies in a different light.[3] Therefore, still the use of conventional surgical drilling templates instead of sophisticated and complex tracking systems for real-time intraoperative navigation seems to be a reliable and reasonable approach for combining the advantages of preoperative computer planning with general implant surgery practice in daily routine.[4,5]

Systems using intraoperative optical tracking cameras are usually referred to as "navigation" or "dynamic" systems. In contrast, systems based on drilling templates are called "template-based" or "static" systems.[6] Static implant planning and positioning is well accepted by dental surgeons as templates are easily integrated into the intraoperative workflow.[7] After incorporation and adaptation of the drilling guide on teeth, bone or mucosa implant holes are conventionally drilled

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through the titanium guiding tubes in the template. For this procedure, an accurate fabrication and stable fixation of the surgical guide is mandatory.

Nowadays, surgical guides for software-assisted implant planning are primarily manufactured on the basis of preoperative advanced image technologies.[8,9] Instead of dynamic navigation systems, which require high-resolution imaging for precise implant placement, template-guided surgery can be performed by the use of cone beam computer tomography (CBCT), also known as digital volume tomography.[10,11] Compared with usual medical multislice computed tomography (MSCT) scanners, CBCT machines are often preferred, because of low costs, easy accessibility, and lower radiation doses.[12] However, produced images disclose also fewer details and also technical-based artifacts are a common feature in today's CBCT images.[13] Spiral as well as CT were initially applied for 3D analysis of complex trauma cases and pathologic lesions.[14] Thereby, CT images were commonly viewed slice per slice in a two-dimensional (2D) axial or coronal orientation through the anatomical region of interest. For the general dentist, these reformatted pictures had only little benefits for precise computer-assisted prosthetic planning of dental reconstructions, as appropriate and necessary software tools were missing to disclose absolute advantages in comparison with conventional 2D radiographs.[15] Nevertheless, growing demand and significant technical advances of 3D imaging for direct and straightforward diagnosis in general practice paved the way for the introduction of novel CBCT systems into oral and maxillofacial implant surgery.[16] In contrast to conventional 2D radiographs, cone beam technology delivered high-quality 3D images with reduced radiation dosages and shortened scanning times.[17] Such pictures allowed the surgeon a complete assessment of hard tissue structures in all dimensions.

With the steady improvement of different 3D imaging systems, refined software packages for virtual planning and placement of dental implants were also introduced on the market.[18,19] Whereas initial software programs in the early 1990 only allowed placement of virtual implants on cross-sectional, axial, and panoramic images of CT scans, later versions enabled the surgeon to exactly plan on 3D reformatted image surface rendering.[20] With these tools, it was easily possible to transfer preoperative virtual implant planning based on a 3D data set to the analogous clinical situation in the mouth of the patient. An additional advantage in this context was the possibility to visualize critical anatomical sites like, for example, the inferior alveolar nerve or sinus floor.[21] Thorough knowledge of anatomic limitations, together with accurate prosthetic-driven preoperative planning, enabled the surgeon to define a predictable and successful treatment plan especially in advanced and complex situations with less bone volume.[22] Nevertheless, one has to carefully keep in mind that a certain deviation between virtual computer planning and the clinical in vivo situation inevitably occurs due to a combination of technical circumstances.[23] Beneath accuracy errors and resolution limitations of imaging systems and software algorithms, incongruities in the manufacturing process of stereolithographic surgical guides play a crucial role for the transferability. Moreover, surgical technique and experience of the surgeon have a vital influence on the overall outcome.

Even though by now the concept of guided surgery for implant therapy is well accepted, still reliable and precise transfer of data remains to be a controversial issue in dental literature.[24–27] Therefore, the aim of the present study was to evaluate the accuracy of dental implant placement using only bone-supported stereolithographic templates in edentulous ridges. The hypothesis was that there are no statistically significant differences in position between virtually planned and clinically placed dental implants. To reduce the accumulation of possible factors influencing impreciseness in the present study, software planning and manufacturing of the drilling guides were performed on multislice CT images.

MATERIALS AND METHODS

Patient Selection

From the patient pool of a private practice in Switzerland, 10 consecutive patients (five women, five men) with a mean age of 62.5 years (range from 47 years to 81 years) were selected for virtual presurgical 3D implant planning using the Facilitate™ software (Astra Tech AB, Mölndal, Sweden). All incoming patients requiring implant-borne dental rehabilitations of edentulous alveolar ridges were allocated from January 2010 to December 2010. All surgical procedures were carried out in accordance with the Helsinki Declaration of 1975, as revised in 2000. Participants had to sign a written

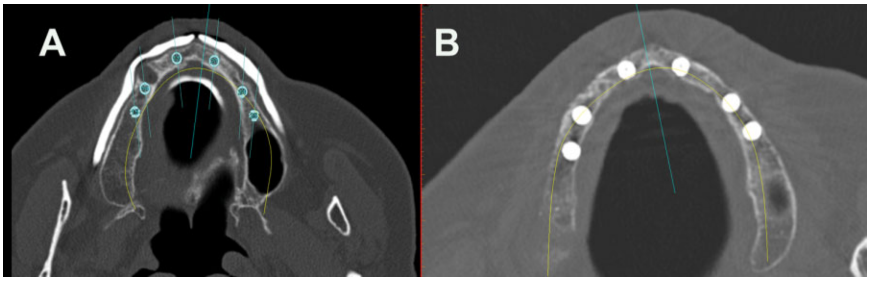

Figure 1 Comparison of pre- and postoperative axial 16-multi-slice CT (16 – MSCT) images with virtually (A) and in vivo (B) places dental implants.

informed consent for the surgical intervention and diagnostic CT. They were informed about the procedure and that corresponding data would be scientifically used. No control group or randomization was included in this clinical trial. All patients were in good systemic health with no contraindications against oral surgical interventions. Prior to surgery, basic evaluation was undertaken including medical history, smoking habits, as well as an examination of the oral cavity. Except heavy smoking (>20 cigarettes per day), no specific contraindications were included. Patients were individually requested to strictly confirm to smoke less than 20 cigarettes per day.

Preoperative and Postoperative CT Imaging

A total of 10 axial 16-MSCT images using high-resolution thin-slice technique were obtained in the preoperative planning setting with a Philips Brilliance 16 channel MSCT (Philips Electronics E.V., Eindhoven, the Netherlands). Scan parameters included 0.8 mm slice thickness reconstruction, 16×0.75 mm, rotation time 0.5 seconds, FOV 180 mm, kV 120, mAs 150, Matrix 512. The region examined in the study was limited to the lower midface below the infraorbital rim and including the complete alveolar process of the maxilla. Axial 0.8 mm slices using a high kernel bone filter (Window settings: C200 W4000) and a soft tissue kernel were reconstructed. The axial plane was adjusted parallel to the level of occlusion, with the gantry tilted to 0°. During CT imaging, patients wore an intraoral radiopaque scan prosthesis that was an exact replica of the definite prosthesis approved by the patient. In addition, in all cases postoperative CT scans, directly performed after surgery, with the same parameters were available for comparative analysis (Figure 1). CT images were converted into digital imaging and further planning of implant position was made using the Facilitate™ software (Astra Tech AB).

Planning, Surgical, and Postsurgical Procedure

After 3D model rendering, software-based implant placement (total $n = 44$) was performed according to bone anatomy and prosthetic design. At least 3 implants (Astra OsseoSpeed ™, Astra Tech AB, Mölndal, Sweden) with a length of 8–11 mm and diameter of 3.5–4.5 mm were virtually installed per patient (Figure 2). The same surgeon who conducted the planning also performed the surgical procedure. He was well experienced in computer-guided implant planning and placement. CT data sets were returned to the manufacturer for production of stereolithographic polymer templates. For a precise surgical execution of planned implant positions

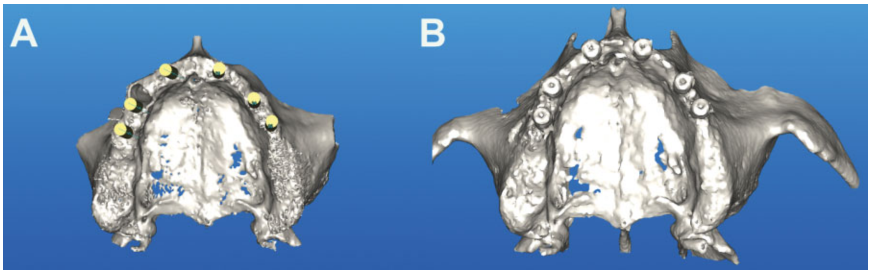

Figure 2 Comparison of software-based implant placement (A: preoperative; B: postoperative) on three-dimensional model rendering with Facilitate™ (Astra Tech AB, Mölndal, Sweden).

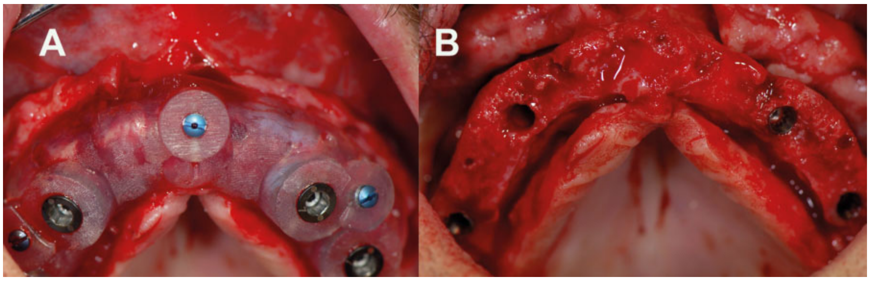

Figure 3 *A*, Intraoperative situation with surgical guides fixed on the edentulous alveolar ridge of the maxilla. *B*, Clinical situation after removal of the template and inserted dental implants. Implants were placed with sub-crestal positions of the implant shoulder of about 0.5 mm.

and angulations into the clinical situation, titanium-guiding tubes were inserted at the positions and artificially elongated axes of final implants in the surgical guides. All templates were exclusively designed for a later skeletal fixation.

One hour before surgery, each patient received a prescription for antibiotics (Aziclav 2 g, Spirig Pharma, Egerkingen, Switzerland; or clindamycin 1200 mg, Sandoz Pharmaceuticals GmbH, Holzkirchen, Germany). Following adequate local anesthesia (Ultracain DS 4% forte, Sanofi-Aventis, Meyrin, Switzerland) and any necessary sedation (Dormicum 7.5–15 mg, Roche Pharma, Reinach, Switzerland), a para-crestal incision with a midline releasing incision in the frontal region was performed in the edentulous ridges under appropriate aseptic and sterile conditions. Additional releasing incisions were placed about 10 mm distally to the last implant. Full mucoperiosteal flaps were carefully raised and the surgical guides were positioned on the supporting skeletal parts of the alveolar ridge (Figure 3). Templates were fixed with equally distributed fixation 2 mm screws (BP System, OBL, Paris, France) with a length of 11–18 mm. Implant insertion (Astra OsseoSpeed™, Astra Tech AB) was executed according to the protocol of the surgical guides using recommended Facilitate™ surgical instruments (Astra Tech AB). To achieve constant sub-crestal positions of the implant shoulder of about 0.5 mm, drill osteotomies were designed at least 0.5 mm deeper than the original implant length. After all implants were seated, the surgical guides were removed and abutments were screwed on. Mucoperiosteal flaps were repositioned and primary wound closure was accomplished with nonresorbable sutures (Dafilon® 4-0, Braun, Melsungen, Germany). Postoperative medication included analgesics and 0.2% chlorhexidine-digluconate mouth rinse for up to 14 days. Follow-up examinations were performed routinely 2 days, 10 days and 6 weeks after surgery. Sutures were removed after 10 days and implants were exposed after 6 weeks.

Accuracy Analysis

In order to evaluate the deviations between the planned and the placed implants, an object registration was performed to pairwise align the preoperative 3D representations of the jaws with their counterparts in the postoperative images according to the technique already introduced and described by D'haese and coworkers (see for details).[28] The same distances and measurements were evaluated in the present study to compare results between mucosally and skeletally supported surgical guides. All operations were performed in the Mimics® software (Materialise, Leuven, Belgium). Global, angular, depth, and lateral deviation parameters were defined and calculated between the planned and the placed implants for the apical and coronal position of the implants (Figure 4). Angle deviations were only determined for different locations (mesial; distal) and not the coronal and the apical positions. The 3D distance between the coronal (or apical) positions was defined as global and the 3D angle between the longitudinal axes of the implants was defined as angular. For the analysis of the lateral deviation, a plane perpendicular to the longitudinal axis of the virtual implant and through its coronal (or apical) position of each implant was defined. The lateral deviation was calculated as the distance between the coronal (or apical) position of the virtual implant and the intersection point of the longitudinal axis of the placed implant with the corresponding plane. Finally, the distance between the coronal (or apical) position of the virtual implant and the intersection point of the longitudinal axis of the implant with a

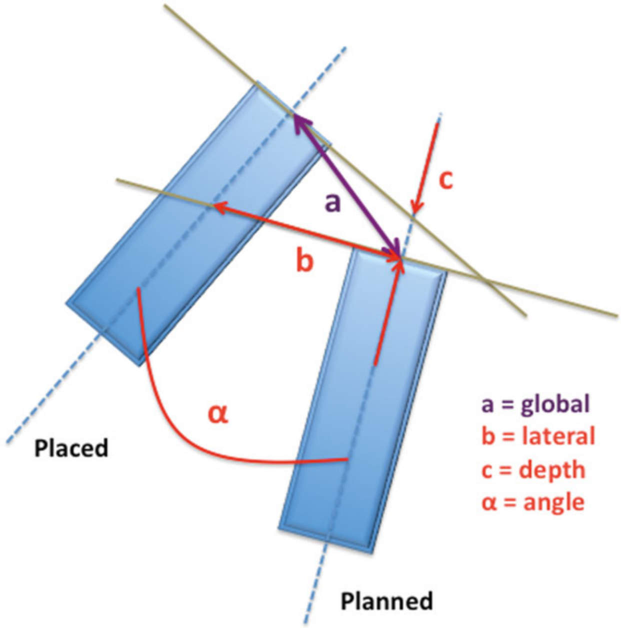

Figure 4 Definition of deviation parameters: global (a), lateral (b), depth (c), and angular (α). The first three deviation parameters (global, lateral, and depth) are presented at coronal level.

plane through the coronal (or apical) point of the placed implant was defined as depth.

Statistical Analysis

Statistical analyses were carried out using SAS Version 9.1.3 (SAS Institute Inc., Cary, NC, USA). A power analysis with $n = 10$ and a standard deviation of 1 revealed a power of 90% (power analysis of a noninferiority test of one mean). Means per locations for all the parameters were presented in a descriptive matter showing percentiles and 95% confidence intervals. The 95% confidence intervals are quite informative as they show how much the means vary. Finally, 1-sample *t*-tests were carried out to test whether the measurements differ from 0. To test for a location effect, that is, more distal location such as 5,6 may yield greater deviations as compared with 3,4 or 1,2 and position effect (apical vs coronal) mixed model analyses were be carried out with each patient treated as random effect for accounting within-patient dependencies (knowing that measurement of implants within the same patient are correlated). Least squares means were presented for adjusted effects. No differentiation between maxilla and mandible was made. Left- and right-hand sides were not considered separately.

RESULTS

Clinical Outcome

Ten consecutive edentulous patients were included in this study. Altogether, 44 implants could be placed without any surgical or prosthetic complications during a follow-up period of 1 year for all 10 patients. No implant was lost and removable prostheses showed stable fixation with no signs of loosening or cracking. All implants could be placed in an absolute parallel alignment to the sagittal plane with the help of the surgical templates. During implant placement, surgical guides allowed a comfortable drilling technique with no incongruity between drills and titanium tubes. Tubes did not detach from the polymer templates. Overall, skeletal support of the templates revealed a reliable and stable fixation. Ball abutments (Astra Tech AB) or LOCATOR®-attachments (Zest Anchors Inc., Escondido, CA, USA) for prosthetic superstructure disclosed comfortable anchorage and retention with a high convenience for the patients. No patient reported any major complaints with regard to the surgical procedure or prosthetic rehabilitation.

Accuracy Analysis

Altogether, 44 implants were evaluated postoperatively by pairwise alignment of the preoperative 3D representations of the jaws with their counterparts in the postoperative images. The 95% confidence intervals of the means of deviations at the coronal position ranged between 0.15 and 1.00 mm (Table 1). They appeared to be greater with distal locations and showed a higher variation (Figures 5–7). Except for depth ($p = .01$), no significant association with location could be detected concerning global ($p = .07$), lateral ($p = .87$), and angular ($p = .56$) values in mixed model analyses (Tables 2–5). The 95% confidence intervals of the means of deviations at the apical position ranged between 0.14 and 1.06 mm (Table 6). There was slight tendency for higher values for more distal locations (Figures 5–7). Yet no statistically significant relation could be detected, except for the depth ($p = .01$) values (Tables 2–5). The 95% confidence intervals of the means of angular deviations ranged between 1.73 and 3.25 grade (Table 7). There was apparently no variation with location (Figure 8 and Table 5).

Overall deviations at the coronal positions appeared to be smaller as compared with those measured at the

TABLE 1 Coronal Position – Deviations by Parameter and Location													
Parameter	Location	N Obs	Mean	Standard Deviation	Median	25% Pctl	75% Pctl	Low 95% CI	Up 95% CI	Min	Max	t-stat.	Pr > ltl
Global	1,2	9	0.61	0.210	0.60	0.45	0.72	0.45	0.77	0.39	1.01	8.75	<0.0001
	3,4	15	0.66	0.402	0.62	0.37	0.75	0.44	0.89	0.20	1.61	6.40	<0.0001
	5,6	20	0.78	0.460	0.78	0.38	0.99	0.57	1.00	0.20	1.77	7.64	<0.0001
	Total	44	0.71	0.399	0.66	0.43	0.86	0.59	0.83	0.20	1.77	11.76	<0.0001
Depth	1,2	9	0.36	0.219	0.35	0.32	0.45	0.19	0.53	0.04	0.73	4.89	0.0012
	3,4	15	0.36	0.389	0.25	0.11	0.46	0.15	0.58	0.01	1.58	3.59	0.0029
	5,6	20	0.60	0.496	0.56	0.17	0.80	0.36	0.83	0.01	1.68	5.37	<0.0001
	Total	44	0.47	0.426	0.35	0.16	0.69	0.34	0.60	0.01	1.68	7.28	<0.0001
Lateral	1,2	9	0.44	0.235	0.39	0.27	0.60	0.26	0.62	0.19	0.91	5.63	0.00049
	3,4	15	0.44	0.367	0.30	0.19	0.57	0.24	0.65	0.04	1.25	4.66	0.00037
	5,6	20	0.41	0.264	0.37	0.22	0.58	0.28	0.53	0.05	1.14	6.88	<0.0001
	Total	44	0.43	0.292	0.36	0.21	0.58	0.34	0.51	0.04	1.25	9.66	<0.0001

apical position. But only the difference with regard to lateral measurements appeared to be statistically significant ($p = .03$) (Table 4).

DISCUSSION

It was the aim of this clinical trial to evaluate the overall deviations between virtually planned and surgically placed dental implants in 10 edentulous alveolar ridges. Analysis was based on a comparison of preoperative and postoperative multislice CT images. In all cases, global deviation, depth deviation, lateral deviation, and angular deviation were determined. The first three parameters were evaluated both for the coronal and the apical parts of the implant positions. Measurements and statistical comparison revealed that deviations at the coronal positions appeared to be smaller as compared with those measured at the apical position. Yet only values of lateral measurements disclosed a significant difference ($p = .03$). Furthermore, mean deviations appeared to be greater for more distal locations.

The higher lateral deviations at the apical position compared with coronal position was according to expectation. It could be explained by the effect of the angular deviation. The angular deviation results in a lateral deviation. This lateral deviation increases with growing distance from the guiding tube. As a consequence, the apical point of the implant is expected to have a larger lateral deviation than the coronal point.

In dental implantology development, integration and clinical validation of cutting-edge technologies for

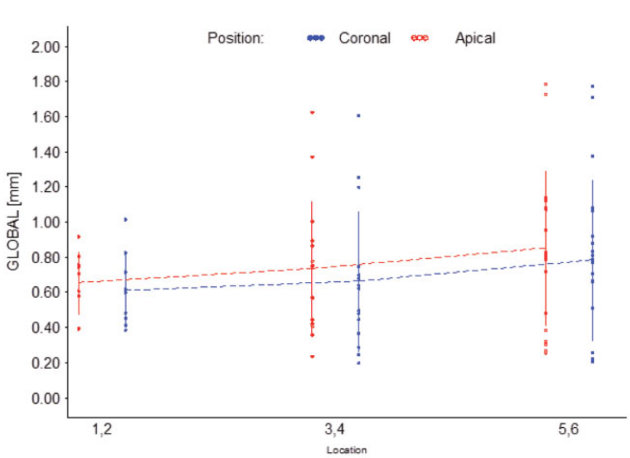

Figure 5 Mean and standard deviation for global measurements.

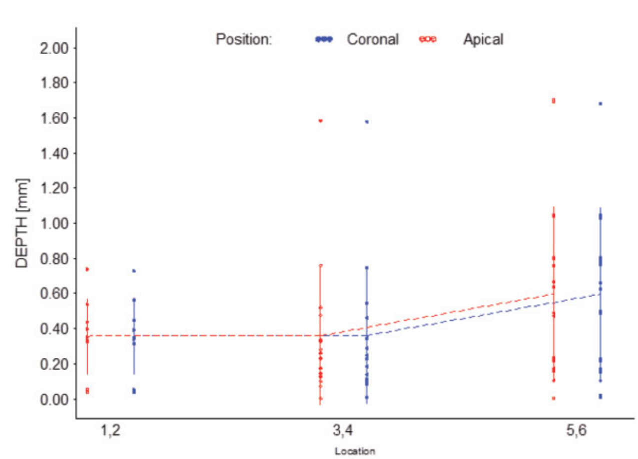

Figure 6 Mean and standard deviation for depth measurements.

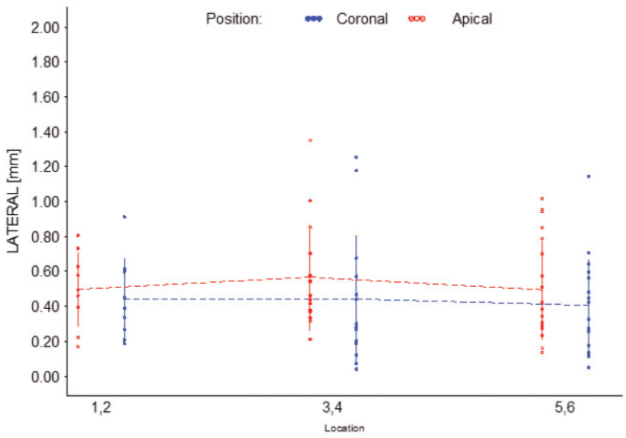

Figure 7 Mean and standard deviation for lateral measurements.

innovative treatment concepts are currently becoming a central part of state-of-the-art dentistry. Implementation of CT imaging, 3D virtual planning software, real-time navigation, robotic assistance, and computer-aided design/computer-assisted manufacture offer unprecedented opportunities and advantages for the surgeon.[29] Reliable transfer of highly accurate 3D planning data into the clinical situation reduces the risk of iatrogenic surgical damage and uncertainty about vital and delicate anatomical structures.[30] This allows precise and projectable surgical procedures like, for example, simplified minimal invasive approaches or flapless surgery.[31,32] In spite of the numerous benefits these technologies offer today, there are still some crucial issues, which have to be

TABLE 2 Mixed Model Analyses for Global Values

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	*F* Value	Pr > F
Position	1	75	0.96	0.3302
Location_c	2	75	2.68	0.0754

Least Squares Means

Effect	Location	Position	Estimate	Standard Error	Lower	Upper
Position		Apical	0.7445	0.09203	0.5612	0.9278
Position		Coronal	0.6802	0.09203	0.4969	0.8636
Location_c	1,2		0.6362	0.1112	0.4147	0.8578
Location_c	3,4		0.6805	0.09820	0.4848	0.8761
Location_c	5,6		0.8204	0.09342	0.6343	1.0065

TABLE 3 Mixed Model Analyses for Depth Values

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	*F* Value	Pr > F
Position	1	75	0.00	0.9971
Location_c	2	75	4.47	0.0147

Least Squares Means

Effect	Location	Position	Estimate	Standard Error	Lower	Upper
Position	Apical		0.4409	0.09920	0.2433	0.6385
Position	Coronal		0.4412	0.09920	0.2436	0.6388
Location_c		1,2	0.3667	0.1201	0.1274	0.6060
Location_c		3,4	0.3669	0.1059	0.1559	0.5780
Location_c		5,6	0.5896	0.1007	0.3889	0.7902

TABLE 4 Mixed Model Analyses for Lateral Values

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	*F* Value	Pr > F
Position	1	75	4.70	0.0334
Location_c	2	75	0.14	0.8708

Least Squares Means

Effect	Location	Position	Estimate	Standard Error	Lower	Upper
Position	Apical		0.5153	0.07050	0.3749	0.6558
Position	Coronal		0.4202	0.07050	0.2798	0.5607
Location_c		1,2	0.4878	0.08211	0.3242	0.6514
Location_c		3,4	0.4613	0.07419	0.3135	0.6091
Location_c		5,6	0.4543	0.07135	0.3121	0.5964

carefully considered before an unlimited use of high-tech systems based on a consistent data structure of imaging, segmentation, simulation, and navigation can be advocated without any restrictions.[33] As up-to-date treatment approaches are often dependent on a mutual and well-defined interaction of different technologies, there are several occasions for possible sources of errors for the final treatment outcome.[34] Two of the most decisive factors that have a vital influence on the fabrication of planning models are the quality and further processing of imaging data, because they are the first and fundamental steps for the subsequent process chain. Several authors analyzed and compared the advantages and limitations of different imaging systems for computer-guided implant planning.[35,36] Recently, Poeschl and coworkers[37] compared cone-beam (CBCT) and conventional MSCT for image-guided dental implant planning. In their study, they used photopolymer-acrylate mandibular models with four integrated metal references markers as anatomical landmark-based registration. After scanning models with both methods, they measured six reciprocal distances in the imaging data sets with three different systems and software. In their final analysis, the authors did not find any statistically significant differences between MSCT and CBCT, and thus concluded that quality of imaging data for dental implant planning are comparable with each other. In contrast Weitz et al.[38] evaluated the influence of CBCT imaging on the accuracy of rapid-prototyping models for surgical templates. The authors compared the final precision of the surgical guides with templates produced on plaster models made out of conventional alginate

TABLE 5 Mixed Model Analyses for Angular Values (Only Location Effect)

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	*F* Value	Pr > F
Location_c	2	32	0.59	0.5626

Least Squares Means

Effect	Location	Estimate	Standard Error	Lower	Upper
Location_c	1,2	2.6819	0.3421	1.9850	3.3788
Location_c	3,4	2.4657	0.2813	1.8927	3.0388
Location_c	5,6	2.3025	0.2571	1.7787	2.8263

TABLE 6 Apical Position – Deviations by Parameter and Location

Parameter	Location	N Obs	Mean	Standard Deviation	Median	25% Pctl	75% Pctl	Low 95% CI	Up 95% CI	Min	Max	t-stat.	Pr > |t|
Global	1,2	9	0.66	0.179	0.71	0.58	0.76	0.52	0.79	0.39	0.92	11.01	<0.0001
	3,4	15	0.74	0.383	0.75	0.42	0.89	0.52	0.95	0.23	1.62	7.44	<0.0001
	5,6	20	0.85	0.441	0.82	0.43	1.10	0.65	1.06	0.25	1.78	8.65	<0.0001
	Total	44	0.77	0.382	0.75	0.43	0.98	0.66	0.89	0.23	1.78	13.42	<0.0001
Depth	1,2	9	0.36	0.218	0.35	0.32	0.44	0.19	0.53	0.04	0.74	4.91	0.0012
	3,4	15	0.36	0.391	0.26	0.13	0.48	0.14	0.58	0.00	1.58	3.56	0.0031
	5,6	20	0.60	0.501	0.56	0.17	0.80	0.36	0.83	0.00	1.70	5.32	<0.0001
	Total	44	0.47	0.429	0.34	0.16	0.70	0.34	0.60	0.00	1.70	7.22	<0.0001
Lateral	1,2	9	0.50	0.215	0.50	0.39	0.63	0.33	0.66	0.17	0.81	6.96	0.00012
	3,4	15	0.57	0.302	0.46	0.37	0.70	0.40	0.73	0.21	1.35	7.26	<0.0001
	5,6	20	0.49	0.282	0.40	0.29	0.74	0.36	0.63	0.13	1.02	7.86	<0.0001
	Total	44	0.52	0.273	0.45	0.31	0.70	0.44	0.60	0.13	1.35	12.64	<0.0001

impressions of the same patients. The authors found intolerable imprecision (1.4–3.1 mm) of the surgical guides made by rapid prototyping based on CBCT data sets. Therefore, they concluded that CBCT does not allow manufacturing of accurate templates for static navigation in dental implantology. In a similar approach using patient-equivalent anatomical models, Dreiseidler et al.[39] scrutinized the influence of three different CBCT systems on the transfer accuracy for computer-aided implantology. Their in vitro analysis demonstrated significant CBCT-dependent variances of implant positions with axes deviation differences of around 0.6^0 and metric apical linear deviations of 550 µm. Yet as study aims and designs as well as applied imaging systems and parameters widely differ between published data, it is currently challenging to draw any conclusions concerning the final accuracy and usability of mainly CBCT for image-guided dental implant planning. According to a recent consensus report, however, CBCT, especially by additional use of radiopaque scanning templates, should be considered as an imaging alternative for interactive software treatment planning.[40] Necessary requirements for a successful implementation are that clinicians should be provided with a profound education and knowledge of imaging, 3D diagnosis, and treatment planning concepts.

Even though imaging technology certainly plays a vital role for possible inaccuracy of data transfer, one should be aware of the fact that, for example, template fabrication, software algorithms, fixation of drilling guides, and surgical performance, also directly contribute to the sources of error. Obviously, experience and technical skills of the surgeon are of major importance. Therefore, Eggers et al.[41] determined the accuracy of template-based dental implant placement involving two surgeons. Overall comparison between test and control boreholes in identical phantom models demonstrated that average longitudinal, lateral errors were less than 0.5 mm and angular deviations less than 5° with the tested system. The choice of surgeon had no significant

TABLE 7 Angular Deviation by Location

	Angular Deviation										Paired *t*-Test	
Location	N Obs	Mean	Standard Deviation	Median	25% Pctl	75% Pctl	Low CL	Up. CL	Min	Max	t-stat.	Pr > |t|
1,2	9	2.49	0.98	2.69	2.08	2.92	1.74	3.25	0.81	4.19	7.61	<0.0001
3,4	15	2.51	0.76	2.51	2.13	2.93	2.08	2.93	0.67	4.12	12.71	<0.0001
5,6	20	2.26	1.12	2.38	1.30	2.99	1.73	2.78	0.53	4.52	8.99	<0.0001
Total	44	2.39	0.97	2.49	1.83	2.92	2.09	2.68	0.53	4.52	16.34	<0.0001

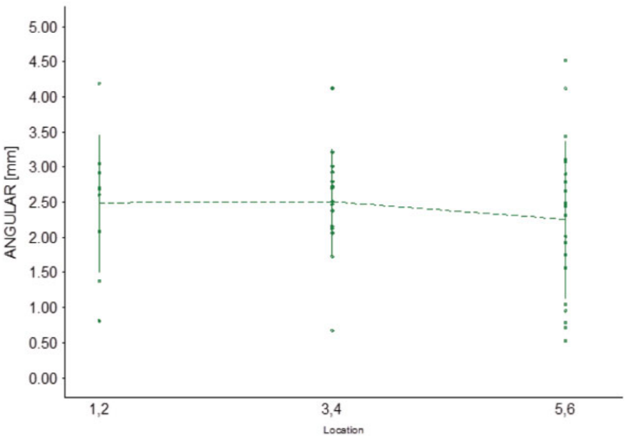

Figure 8 Mean and standard deviation for angular measurements.

influence. Therefore, the authors concluded that the use of templates offered a high and reproducible accuracy.

Another critical aspect beneath operating experience is the fixation method and intraoral fitting of templates. Surgical guides can be either supported by mucosa or on teeth or bone. Although skeletal or dental fixation provides a sound footing for surgical guides, Di Giacomo et al.[42] reported mean deviations of 1.45 mm at the implant shoulder and 2.9 mm at the apex between virtually planned and placed dental implants in patients. These results are in accordance with the present study and results of Van Assche and coworkers[43] (mean coronal: 1.1 mm; mean apical: 1.2 mm), which also demonstrated higher deviations at the apical part than at the coronal part. In contrast to the aforementioned studies, D'haese et al.[26] analyzed the accuracy of mucosally supported stereolithographic surgical guides which intrinsically bear a higher risk of possible inaccuracy. The authors used a 64-slice dual source CT scan for imaging and the same planning software Facilitate™ and dental implant system (Astra Tech AB). A 3D evaluation and measurement of deviations of virtually planned and in vivo placed implants was performed in the same manner. Average angle deviation was 2.60° (present study: 2.39°) and mean global apical deviation was 1.13 mm (present study: 0.77°). Mean global coronal deviation was 0.91 mm and thus like in the current study (0.71 mm) less than apical deviation. Although fixation of surgical guides (mucosa vs bone) was different, in both studies a higher level of inaccuracy for the apical part of the implants was obvious. Furthermore, mean deviations appeared to be greater for more distal locations and showed a higher variation. Thus, precision was more difficult to reach for more distal locations. Interestingly, even though for the mucosal-supported templates a 64-slice CT, the same planning software, and analogous stereolithographic template manufacturing were used, final results showed a clear tendency for higher deviations than in the present study. This clearly proves that sources of inaccuracy errors for the treatment outcome are prone to occur at each step of the planning and surgical protocol. The tendency of higher deviations for mucosa-supported guides than for bone-supported guides is to be expected. The mucosa is due to its compressibility a less stable supporting surface than the bone surface, and as a consequence more error prone.

Moreover, also bone structure and design of dental implants have an impact on potential variations between planning and in vivo position of dental implants. Especially in soft and trabecular bone, slight axe deviations of originally intended implant positions are more likely to occur, because of less torque resistance in contrast to cortical structures. This will certainly allow easier mechanical compression at the lateral aspect of the osteotomy sites and thus variation of angulation. Implants will not automatically follow the route of the guiding drill hole. In this respect, body shape and thread design may also lead to slight deviations, as initial incongruities with less frictional guidance of, for example, conical implants, allow a loose fit. Therefore, a centric and fixed parallel drilling by the help of stable guiding tubes helps to reduce the accumulation of inaccuracy factors.[44]

CONCLUSION

To transfer the most ideal implant position from software-based virtual planning models to the in vivo situation, the summation effect of factors influencing the accuracy have to be carefully considered. Thus individual errors may not only base on initial imaging scans, but also on all further planning, manufacturing, and surgical steps. As deviations between planned and placed implants are obviously inevitable even in case of proper application and knowledge of state-of-the-art technologies for computer-guided implant surgery, the clinician should be aware not to overestimate advocated surgical safety by using static navigation tools.

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REFERENCES

1. Katsoulis J, Pazera P, Mericske-Stern R. Prosthetically driven, computer-guided implant planning for the edentulous maxilla: a model study. Clin Implant Dent Relat Res 2009; 11:238–245.
2. Schiroli G, Angiero F, Silvestrini-Biavati A, et al. Zygomatic implant placement with flapless computer-guided surgery: a proposed clinical protocol. J Oral Maxillofac Surg 2011; 69:2979–2989.
3. Jung RE, Schneider D, Ganeles J, et al. Computer technology applications in surgical implant dentistry: a systematic review. Int J Oral Maxillofac Implants 2009; 24:92–109.
4. Park C, Raigrodski AJ, Rosen J, et al. Accuracy of implant placement using precision surgical guides with varying occlusogingival heights: an in vitro study. J Prosthet Dent 2009; 101:372–381.
5. Ewers R, Seemann R, Krennmair G, et al. Planning implants crown down – a systematic quality control for proof of concept. J Oral Maxillofac Surg 2010; 68:2868–2878.
6. Hämmerle CH, Stone P, Jung RE, et al. Consensus statements and recommended clinical procedures regarding computer-assisted implant dentistry. Int J Oral Maxillofac Implants 2009; 24:126–131.
7. Neugebauer J, Stachulla G, Ritter L, et al. Computer-aided manufacturing technologies for guided implant placement. Expert Rev Med Devices 2010; 7:113–129.
8. Ganz SD. CT-derived model-based surgery for immediate loading of maxillary anterior implants. Pract Proced Aesthet Dent 2007; 19:311–318.
9. Spector L. Computer-aided dental implant planning. Dent Clin North Am 2008; 52:761–775.
10. Ganz SD. Computer-aided design/computer-aided manufacturing applications using CT and cone beam CT scanning technology. Dent Clin North Am 2008; 52:777–808.
11. Ganz SD. Cone beam computed tomography-assisted treatment planning concepts. Dent Clin North Am 2011; 55:515–536.
12. De Vos W, Casselman J, Swennen GR. Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. Int J Oral Maxillofac Surg 2009; 38:609–625.
13. Schulze R, Heil U, Gross D, et al. Artefacts in CBCT: a review. Dentomaxillofac Radiol 2011; 40:265–273.
14. Schuknecht B, Graetz K. Radiologic assessment of maxillofacial, mandibular, and skull base trauma. Eur Radiol 2005; 15:560–568.
15. Yune HY. Two-dimensional-three-dimensional reconstruction computed tomography techniques. Dent Clin North Am 1993; 37:613–626.
16. Pette GA, Norkin FJ, Ganeles J, et al. Incidental findings from a retrospective study of 318 cone beam computed tomography consultation reports. Int J Oral Maxillofac Implants 2012; 27:595–603.
17. Kau CH, Bozic M, English J, et al. Cone-beam computed tomography of the maxillofacial region – an update. Int J Med Robot 2009; 5:366–380.
18. Abboud M, Wahl G, Guirado JL, et al. Application and success of two stereolithographic surgical guide systems for implant placement with immediate loading. Int J Oral Maxillofac Implants 2012; 27:634–643.
19. Vasak C, Watzak G, Gahleitner A, et al. Computed tomography-based evaluation of template (NobelGuide™)-guided implant positions: a prospective radiological study. Clin Oral Implants Res 2011; 22:1157–1163.
20. Orentlicher G, Abboud M. Guided surgery for implant therapy. Dent Clin North Am 2011; 55:715–744.
21. McNamara C, House K, Davies R, et al. The current status of 3D imaging in dental practice. Dent Update 2011; 38:679–682.
22. Timock AM, Cook V, McDonald T, et al. Accuracy and reliability of buccal bone height and thickness measurements from cone-beam computed tomography imaging. Am J Orthod Dentofacial Orthop 2011; 140:734–744.
23. Jabero M, Sarment DP. Advanced surgical guidance technology: a review. Implant Dent 2006; 15:135–142.
24. Schneider D, Marquardt P, Zwahlen M, et al. A systematic review on the accuracy and the clinical outcome of computer-guided template-based implant dentistry. Clin Oral Implants Res 2009; 20:73–86.
25. Widmann G, Bale RJ. Accuracy in computer-aided implant surgery – a review. Int J Oral Maxillofac Implants 2006; 21:305–313.
26. D'haese J, Van De Velde T, Komiyama A, et al. 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 2012; 14:321–335.
27. Komiyama A, Pettersson A, Hultin M, et al. Virtually planned and template-guided implant surgery: an experimental model matching approach. Clin Oral Implants Res 2011; 22:308–313.
28. D'haese J, Van De Velde T, Elaut L, et al. A prospective study on the accuracy of mucosally supported stereolithographic surgical guides in fully edentulous maxillae. Clin Implant Dent Relat Res 2012; 14:293–303.

29. de Almeida EO, Pellizzer EP, Goiatto MC, et al. Computer-guided surgery in implantology: review of basic concepts. J Craniofac Surg 2010; 21:1917–1921.
30. Rosenfeld AL, Mandelaris GA, Tardieu PB. Prosthetically directed implant placement using computer software to ensure precise placement and predictable prosthetic outcomes. Part 1: diagnostics, imaging, and collaborative accountability. Int J Periodontics Restorative Dent 2006; 26:215–221.
31. Rosenfeld AL, Mandelaris GA, Tardieu PB. Prosthetically directed implant placement using computer software to ensure precise placement and predictable prosthetic outcomes. Part 2: rapid-prototype medical modeling and stereolithographic drilling guides requiring bone exposure. Int J Periodontics Restorative Dent 2006; 26:347–353.
32. Rosenfeld AL, Mandelaris GA, Tardieu PB. Prosthetically directed implant placement using computer software to ensure precise placement and predictable prosthetic outcomes. Part 3: stereolithographic drilling guides that do not require bone exposure and the immediate delivery of teeth. Int J Periodontics Restorative Dent 2006; 26:493–499.
33. Di Giacomo GA, da Silva JV, da Silva AM, et al. Accuracy and complications of computer-designed selective laser sintering surgical guides for flapless dental implant placement and immediate definitive prosthesis installation. J Periodontol 2012; 83:410–419.
34. Pettersson A, Komiyama A, Hultin M, et al. Accuracy of virtually planned and template guided implant surgery on edentate patients. Clin Implant Dent Relat Res 2010. DOI: 10.1111/j.1708-8208.2010.00285.x.
35. Vercruyssen M, Jacobs R, Van Assche N, et al. The use of CT scan based planning for oral rehabilitation by means of implants and its transfer to the surgical field: a critical review on accuracy. J Oral Rehabil 2008; 35:454–474.
36. Loubele M, Van Assche N, Carpentier K, et al. Comparative localized linear accuracy of small-field cone-beam CT and multislice CT for alveolar bone measurements. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 105:512–518.
37. Poeschl PW, Schmidt N, Guevara-Rojas G, et al. Comparison of cone-beam and conventional multislice computed tomography for image-guided dental implant planning. Clin Oral Investig 2012. DOI: 10.1007/s00784-012-0704-6.
38. Weitz J, Deppe H, Stopp S, et al. Accuracy of templates for navigated implantation made by rapid prototyping with DICOM datasets of cone beam computer tomography (CBCT). Clin Oral Investig 2011; 15:1001–1006.
39. Dreiseidler T, Tandon D, Kreppel M, et al. CBCT device dependency on the transfer accuracy from computer-aided implantology procedures. Clin Oral Implants Res 2012. DOI: 10.1111/j.1600-0501.2011.02272.x.
40. Benavides E, Rios HF, Ganz SD, et al. Use of cone beam computed tomography in implant dentistry: the International Congress of Oral Implantologists consensus report. Implant Dent 2012; 21:78–86.
41. Eggers G, Patellis E, Mühling J. Accuracy of template-based dental implant placement. Int J Oral Maxillofac Implants 2009; 24:447–454.
42. Di Giacomo GA, Cury PR, de Araujo NS, et al. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. J Periodontol 2005; 76:503–507.
43. 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.
44. Van Assche N, Quirynen M. Tolerance within a surgical guide. Clin Oral Implants Res 2010; 21:455–458.