Accuracy in Computer-Aided Implant Surgery—A Review

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The objective of this article was to review the different factors and limitations influencing the accuracy of computer-aided implant surgery. In vitro and in vivo accuracy studies of articles and congress proceedings were examined. Similar results using bur tracking as well as image-guided template production techniques have been reported, and both methods allow for precise positioning of dental implants. Compared to the conventional technique, this sophisticated technology requires substantially more financial investment and effort (computerized tomographic imaging, fabrication of a registration template, intraoperative referencing for bur tracking, or image-guided manufacturing of a surgical template) but appears superior on account of its potential to eliminate possible manual placement errors and to systematize reproducible treatment success. The potential for the protection of critical anatomic structures and the esthetic and functional advantages of prosthodontic-driven implant positioning must also be considered. However, long-term clinical studies are necessary to confirm the value of this strategy and to justify the additional radiation dose, effort, and costs. (More than 50 references) (Literature Review) Int J Oral Maxillofac Implants 2006;21:305–313

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The implant-supported oral restoration has become an increasingly used treatment option for edentulous and partially edentulous patients. Even in patients with severe bone atrophy and in locations previously considered unsuitable for implants, implant treatment has been made possible through sophisticated reconstruction techniques, including sinus augmentation, distraction osteogenesis, bone grafting, and tissue regeneration.[1–4] More than 30 years of experience have refined the material involved as well as the planning and surgical procedure.

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Historically, dental surgeons tended to place implants where the greatest amount of bone was present, with less regard to placement of the definitive restoration. The clinical outcome and long-term prognosis of implant-supported oral restorations largely depends on the stable and firm fixation of dental implants in the bone. However, disregarding prosthetic demands often leads to a compromised definitive prosthesis with a jeopardized occlusal scheme, poor esthetics, or unfavorable biomechanics.[5–8]

Recently, a philosophy of prosthodontic-driven implant placement has been adopted as a treatment modality that combines functional and esthetic concepts.[9,10] In prosthodontic-driven implant placement, diagnostic casts and the diagnostic waxup of the prosthodontic restoration guide the planning of the positions of the proposed implants.[11] To precisely transfer the plan to the operative site, customized radiographic and surgical templates have become a routine part of treatment.[9,12–14] A thorough radiographic examination and exact diagnosis of the bony architecture are fundamental prerequisites.[15,16] Conventional dental panoramic tomography and plain film tomography are usually performed with the patient wearing a radiographic template with integrated metal spheres at the position of the waxup. Based on the magnification factor and the known dimensions of the metal sphere, the depth and dimensions of the implants are planned. However, radiography, which is widely used, has important diagnostic limitations, such as expansion and distortion, setting error, and position artifacts. Radiography does not show lingual blood vessels or provide complete 3-dimensional (3D) information of the dental arch.[16–18] Although conventional surgical templates will allow guiding the bone entry of the drill, they do not provide exact 3D guidance. The templates are fabricated on the diagnostic cast without knowledge of the exact anatomy below the surface. Thus, when conventional implantation techniques are used, the clinical outcome is often unpredictable, and even if the implants are well placed, the location and deviation of the implants may not meet the optimal prosthodontic requirements.

To overcome these limitations, computed tomography (CT), 3D implant planning software, image-guided template production techniques, and computer-aided surgery have been introduced.[15,16,19,20] In CT, multiplanar reformatting (MPR) allows one to reformat a volumetric dataset in axial, coronal, and sagittal cuts and to build multiple cross-sectional and panoramic views.[21,22] Shaded surface display (SSD) and volume rendering methods generate 3D reconstructions of the complete dental arch and relevant structures, including nerves. These advantages make dental CT the most precise and comprehensive radiologic technique for dental implant planning.[15,23,24] Special planning software has been adapted to allow practitioners to virtually plan location, angle, depth, and diameter of virtual implants, which are superimposed on the 3D data set. Following backward planning, the diagnostic waxup has to be visualized on the CT scan through radiographic templates.[14,25] The radiographic templates are fabricated as an exact replica of the desired prosthetic end result and is supported with different radiopaque markers such as gutta percha balls and stripes,[10,26] metal pins and tubes,[27,28] radiopaque varnishes,[25,29] or lead foil.[30,31] Based on the information of the visible waxup dental implants are planned on the CT data with respect to vital structures such as the mandibular nerve, the maxillary sinus, and the roots of adjacent teeth.[13,32,33]

Different approaches to image-guided dental implant placement have been introduced to precisely transfer the planning data to the operative site. Mechanical positioning devices or drilling machines convert the radiographic template to a surgical template by executing a computerized transformation algorithm.[5,34–36] CAD-CAM (computer-aided design/computer-aided manufacturing) rapid prototyping techniques generate stereolithographic templates,[20,37–39] and bur tracking allows for intraoperative real-time tracking of the drill according to the planned trajectory.[40–42] In addition, surgical microscopes and head-mounted displays (HMD) are used to project the virtual plan into the real optical path; the displayed target structures are then followed with the bur drill.[43,44] Bur tracking and image-guided template production have been clinically tested and are on the way to being established as routine clinical treatment options.[20,42] However, the use of such techniques raises important questions: How accurate is image guidance? To what extent is it better than standard procedure? What is the cost-benefit ratio? The aim of this review was to explore the limitations of accuracy in computer-aided dental implant surgery and to discuss the cost-benefit ratio.

ASPECTS OF ACCURACY

The accuracy of an image-guided procedure is defined as the deviation in location or angle of the plan compared to the result and includes all possible single errors from image acquisition to surgical implant positioning. The errors are cumulative and interactive.

Accuracy of Image Acquisition

Accurate assessment of bony architecture and measurements of anatomic structures are prerequisites for appropriate implant planning.[45] In general, the quality of CT data depends on the slice thickness and the influence of possible artifacts. The thinner the slice thickness and the smaller the voxel size, the higher the resolution and accuracy of measurements of delineated structures.[46–48] Movement and metallic artifacts of dental restorations may lead to geometric distortions and invalid data acquisition.

Solar and colleagues[49] performed 2,664 measurements comparing reformatted axial CT slices of 37 human jaw specimens (slice thickness 1.5 mm and table feed 1 mm) to corresponding native cuts of the specimens. The horizontal measurements (the x and y axes) showed a mean discrepancy of 0.29 ± 0.32 mm (mean ± SD), and the vertical measurements (z axis) on the CT scans showed discrepancies of 0.65 ± 0.43 mm compared to the native specimen. The mean error in the z axis (table feed) was higher than in the plane of the originally acquired data. This must be kept in mind when planning the length of implants. The authors stated that one of the reasons for the discrepancies was difficulty in reproducible definition of the landmarks.

Using glass sphere reference markers placed in the mandibular plane, as proposed by Reddy and associates,[50] the mean accuracy of vertical and horizontal measurements on 2D reformatted CT views (slice thickness 1.5 mm, fixed slice spacing 1.0 mm, and 0.5 mm overlap of each slice) varied from 0.07 to 0.15 mm. The results were significantly better than those observed on even the best-positioned panoramic radiographs, where accuracy ranged from 0.15 to 0.24 mm following 25% magnification correction. The difference was strikingly higher when placement was not optimal, which indicates that the standard practice of assuming a consistent 25% magnification for dental panoramic radiography may need reconsideration.

No significant differences in precision (reproducibility) or accuracy (validity) of 3D volume rendered images from multislice spiral CT data sets (slice thickness 0.5 mm, 0.5 mm table feed, and 0.5-mm interval reconstructions) were observed between either inter- or intraobserver measurements or between in vitro and in vivo measurements. A difference of 0.25 mm was found between the mean actual (native) and mean 3D-based linear measurements.[51] In conclusion, multislice spiral CT is the most accurate radiographic means for dental implant planning.

Accuracy of Registration

The precise transfer of virtual planning to the surgical site depends on the accuracy of the registration procedure. This is known as the image-to-physical (IP) transformation. It depends on 1-to-1 mapping between the coordinates in 1 space (image data) and those in another (physical space; the patient); points in the 2 spaces that correspond to the same anatomic point must be mapped to each other.[52] Navigation systems used for image-guided bur tracking rely on point-based (fiducial) registration. Anatomic landmarks cannot be exactly and reproducibly defined with appropriate accuracy.[53] Registration with skin fiducials is sensitive to skin shift and requires complex logistics, since the markers have to be placed prior to data set acquisition and have to be maintained in position until the patient enters the operating room.[54,55] As dental implant surgery requires the most accurate registration, IP transformation using anatomic landmarks (bone or skin) or skin fiducials is inappropriate. Therefore, implanted bone markers or noninvasive registration templates that are attached to the remaining teeth are used for image-guided bur tracking.[42,56,57]

To analyze the accuracy of point-based registration methods, the following measures of error have been suggested[52,58,59]: Fiducial localization error (FLE), which is the error in locating the fiducial points; fiducial registration error (FRE), which is the root-mean-square distance between corresponding fiducial points after registration; and target registration error (TRE), which is the distance between corresponding points other than the fiducial points after registration. Using 3 implanted fiducials on jaw models, Birkfellner and colleagues[60] found a mean FLE of 0.69 mm, a mean FRE of 0.7 mm, and a mean TRE of 1.2 mm. Bone fiducials require an invasive procedure and should not be left in place over an extended period.

As an alternative, registration templates can be attached to the dental arch for data acquisition and initial IP transformation. Using a registration template with 5 titanium fiducial miniscrews, Schneider and associates[61] found an experimentally determined mean accuracy of 0.68 mm. The process they used included CT data acquisition, registration, and dynamic tracking. The use of registration templates may introduce another source of error, as there may be undetected loosening of the modified impression tray. In edentulous patients, firm fixation of the template must be guaranteed by bone screws.

A problem with orally situated markers (invasive or template-supported) is that in extended prosthetic restorations with fixed partial dentures or dental crowns, metallic artifacts may lead to difficulties in marker identification and IP transformation. The expected TRE is worst near the fiducials that are most closely aligned; broad distribution of the reference markers around the region of interest is required.[58] Marmulla and coworkers[55] reported that during data acquisition, markers may get in between 2 CT slices, which can result in incorrect marker correlation on the CT data and lead to false target measurements and geometric rotation of the registered data set compared to the anatomic data. Thus, the slice thickness should be as small as possible, and the markers should be as large as possible (sufficiently larger then a voxel).[52] The typical feedback provided by registration software is a measure of the degree of alignment of the points used in the registration. Unfortunately, these measures show no direct correlation to the TRE. Thus, fiducial alignment should not be trusted as the sole indicator of registration success of a point-based guidance system.[62] For safety reasons and for reliable control of the registration accuracy, the real error between the image and the patient's anatomy must be checked prior to surgery by an independent marker not used for initial registration or using anatomic landmarks.[41,56] This can be performed with the probe of the navigation system by comparing the probe's real position to the virtual position displayed on the computer screen.

Table 1 Accuracy of Bur Tracking and IGTP

	n	Accuracy	Range	Maximum	Evaluation	In vitro/ in vivo	Technique
Schneider et al[61]	100	[x,y]: 0.68 ± 0.63 mm			Image fusion	In vitro	Bur tracking
Brief et al[65]	38	Base [x]: 0.5 mm		1.1 mm	Image fusion	In vitro	Bur tracking
		[y]: 0.3 mm		0.9 mm			
		Tip [x]: 0.6 mm		1.1 mm			
		[y]: 0.3 mm		1.0 mm			
		[z]: 0.2 mm		0.7 mm			
Schermeier et al[66]	24	Base [x,y]: 0.08 ± 0.41 mm			Digital slide gauge	In vitro	Bur tracking
		0.98 ± 1.44 degrees					
Wanschitz et al[67]	20	Base [lingual]: 0.49 ± 0.38 mm	0.0–1.4 mm		Image fusion	In vitro	Bur tracking
		[buccal]: 0.55 ± 0.31 mm	0.1–1.5 mm				
		Tip [lingual]: 1.36 ± 0.70 mm	0.0–3.2 mm				
		[buccal]: 1.44 ± 0.79 mm	0.2–3.5 mm				
Wanschitz et al[68]	15	Base [lingual]: 0.57 ± 0.49 mm	0.0–1.8 mm		Image fusion	In vitro	Bur tracking
		[buccal]: 0.58 ± 0.40 mm	0.0–1.4 mm				
		Tip [lingual]: 0.77 ± 0.63 mm	0.0–2.9 mm				
		[buccal]: 0.79 ± 0.71 mm	0.1–3.1 mm				
		3.55 ± 2.07 degrees	0.9–10.4 degrees				
Wagner et al[69]	32	Base [lingual]: 1.0 ± 0.7 mm	0.0–2.6 mm		Image fusion	In vivo	Bur tracking
		[buccal]: 0.8 ± 0.5 mm	0.0–2.1 mm				
		Tip [lingual]: 1.3 ± 0.9 mm	0.0–3.5 mm				
		[buccal]: 1.1 ± 0.9 mm	0.0–3.4 mm				
		6.4 ± 3.6 degrees	0.4–17.4 degrees				
Besimo et al[19]	26	Tip [maxilla]: 0.6 ± 0.4 mm	0.0–1.5 mm		Postoperative CT	In vitro	IGTP
	51	Tip [mandible]: 0.3 ± 0.4 mm	0.0–1.4 mm				
Naitoh et al[70]	21	Base: 0.3 ± 0.6 mm	0.0–2.0 mm		Milling machine	In vivo	IGTP
		5.0 ± 3.5 degrees					
van Steenberghe et al[37]		Base: 0.8 ± 0.3 mm		1.1 mm	Image fusion	In vitro/ in vivo	IGTP CAD/ CAM
		Tip: 1.0 ± 0.6 mm					
		1.8 ± 1.0 degrees					
Sarment et al[39]	25	Base: 0.9 ± 0.5 mm	0.7–1.2 mm		Image fusion	In vitro	IGTP CAD/ CAM
		Tip: 1.0 ± 0.6 mm	0.7–1.6 mm				
		4.5 ± 2.0 degrees					
Chen et al[71]	30	Base: 0.75 ± 0.15 mm			Image fusion	In vivo	IGTP CAD/ CAM
		Tip: 1.36 ± 0.28 mm					

IGTP = image-guided template production.
IGTP CAD/CAM denotes sterolithographic surgical templates.

For intraoperative navigation, continuous referencing of an unfixed patient is required. A dynamic reference frame is directly secured to the underlying bone or attached to a tooth-fixed registration template. By these means, movements of the patient's jaw with respect to the camera array are corrected in real time.[40–42] Naturally, a rigid fixation of the tracking device has to be guaranteed for the duration of the treatment. The reference markers on the patient tracking device should not be situated too far from the surgical site, as the precision decreases with increasing distance.[55,56]

IP transformation for image-guided template production differs from IP transformation for bur tracking. The patient's dental stone cast is registered rather than the patient. Building blocks, reference tubes, or pins are integrated in a registration template and are recognized by the software in the CT scan. The 3D implant planning is transferred into a surgical template by a mechanical positioning device, by a drilling machine, or by rapid prototyping, which executes a computerized transfer algorithm or specific angular measures.[5,36,57,63,64] Similar to bur tracking, safety pins must be used to independently check the registration accuracy.

Accuracy of Navigation and Surgical Template Production

The precision of the surgical transfer itself depends on the systematic and application accuracy of the individual technique used. Data on the accuracy of image-guided template production and image-guided bur tracking, as reported in the literature, is displayed in Table 1.

Most studies were evaluated by comparing the postoperative CT data with the planning data set through image fusion using the mutual information technique. In this technique, the scans are interpolated to isotropic voxel size and matched by comparing the similarity of neighboring voxels in the volume image.[67] Besimo and associates[19] found mean accuracies of surgical templates obtained by a drilling machine of 0.6 mm for the maxilla and 0.3 mm for the mandible, with a maximum deviation of 1.5 mm. van Steenberghe and associates[37] reported mean accuracies of rapid prototyping templates of 0.8 mm at the base and 0.9 mm at the tip of the implant, which are comparable to the results of Sarment and colleagues.[39] In image-guided bur tracking, Wanschitz and coworkers[67] found mean accuracies of 0.5 to 0.6 mm at the base (maximum deviation 1.5 mm) and about 1.4 mm at the tip (maximum deviation 3.5 mm). Similar results were found for bur tracking guided by head-mounted displays.[68]

Some authors have applied different evaluation methods, which makes it difficult to compare the results. Schermeier and coworkers[66] used a digital slide gauge and a reference brick, Naitoh and colleagues[70] used the milling machine for angular measures, and Fortin and associates[72] reported the Kendall correlation coefficient for qualitative data and the Kappa concordance coefficient for quantitative data. However, when accuracy data for bur tracking were compared with accuracy data for template production techniques evaluated by the same method, lower precision at the tip of the implant was found for bur tracking. The differences in the mean values were about 0.4 mm, and most importantly, the difference in maximum deviation rose to approximately 2 mm (1.6 mm for templates versus 3.5 mm for bur tracking).

One must carefully distinguish between the accuracy achieved at the base of the implant and the accuracy achieved at the tip. Accuracy at the tip is more important, as the tip is situated in the vicinity of vital anatomic structures. Naturally, the accuracy at the base is always better because of the lack of angular deviation which is added by drilling further into the bone.

In vitro studies evaluate the system's technical accuracy, but in vivo studies point out the achieved clinical result, which is influenced by additional aspects. Comparing in vivo to in vitro results of image-guided template production, no relevant differences in accuracy were observed at the implant base. However, for the tip of the implant, differences of about 0.4 mm were found. Comparing in vivo to in vitro results of bur tracking, differences in accuracy of 0.2 to 0.5 mm for the base and 0.3 to 0.5 mm for the tip were found.

In image-guided template production, errors may be the result of unstable fixation of the surgical template. Precise mechanical fitting of the template into the patient's mouth (or to the dental stone cast in case of an in vitro study) is of major importance, as the template is fabricated using the dental stone casts of the patient. Naturally, accurate dental impressions and dental stone casts are required. For appropriate use in edentulous patients or in extensive distal free-end situations, it is necessary to secure the templates to the underlying bone by fixation screws.[20] As an alternative, bone-supported rapid prototyping templates can be used. To obtain optimal drilling accuracy, optimal tuning of the single components involved is required, and the bur tubes must be precisely adapted to the dimensions of the pilot drill. If the bur tube diameter is too large, imprecise drilling results as the angular deviation increases along the depth.

An advantage of bur tracking is that the drill is continuously visualized on a computer screen in all 3 dimensions (x, y, and z). As template-based techniques lack interactive control, modifications during the operative procedure are not possible,[60] which makes meticulous and exact preoperative planning a prerequisite for image-guided template production. While the drill guides control angulations (x/y), the location of the drill relative to underlying structures (z) remains uncertain to a considerable degree and needs to be carefully controlled by depth gauges or a stop on the drill. However, the planning software allows for precise measurement of the depth of the virtual implant and the distance to vital structures. These data can be displayed in relation to the bone entrance or the top of the surgical bur tube to allow for intraoperative control through conventional depth gauges.

In contrast to bur tracking, where every drilling of the implant set is executed under navigated control, image-guided template production guides the pilot drilling only, a fact that may influence accuracy.[19,37] A set of consecutive stereolithographic templates or the use of metallic cylinders with different diameters that exactly match the series of drills may overcome this problem.[18,37,39] Furthermore, specially designed drills with proximal non-cutting pilot extensions enhance the accuracy of the drillings even if they are not directly guided by a template.[73]

Human Error

Human error is attributed to all imaging, planning, and transfer errors. Thus, every step has to be carefully managed. Thorough positioning of registration devices, motionless CT data acquisition, precise planning, verification of registration accuracy, and constant attention to stable and precise fit of the registration template or dynamic reference frame is required. As bur tracking involves hand tremor and perception inaccuracies of about 0.25 mm and 0.5 degrees,[74] clinical success is dependent on the skill of the dental surgeon to interpret and execute positional data displayed on the computer screen during drilling of the implant socket.[68] Later, technology may link drill speed to operator accuracy. When the position and angle of the bur stand outside a certain degree of accuracy, the drill will slow down or automatically stop before reaching a vital anatomic structure. In image-guided template production, a prefabricated template is obtained, which makes the procedure less dependent on the surgeon's navigational expertise. However, great attention must be paid to consecutive drillings not guided through the template.

Navigation-controlled techniques are considered to be less influenced by human error than standard implantation methods. When comparing accuracy measurements of an experienced implant surgeon executing freehand drillings without navigation to navigated drillings into a rectangular test body, a mean x/y deviation of 6.1 mm (maximum 7.2 mm) was found for the freehand drillings and 0.5 mm (maximum 1.2 mm) for the navigated drillings.[74] Although this investigation was performed under artificial conditions and did not correspond to the oral situation, where at least some anatomic orientation is possible, a freehand accuracy of less than 3 mm seems unrealistic. Comparing the in vivo use of a conventional surgical template to a CT-guided stereolithographic template, Sarment and associates[39] found means of 1.5 mm (base) and 2.1 mm (tip) for the conventional guide and 0.9 mm (base) and 1.0 mm (tip) for the stereolithographic guide. Navigated drillings showed significantly enhanced precision compared to freehand placements, even when the freehand placements were performed by experienced surgeons. To test the predictability of the navigational procedure, Schermeier and colleagues[74] further compared an experienced implant surgeon without any training on navigational systems and an engineer who was familiar with 3-dimensional computer navigation. No significant difference was found, which demonstrates that image guidance is a valuable means for achieving a predictable and reproducible result without heavy reliance on the clinician's surgical experience. Kramer and coworkers[75] compared navigated and conventional implant placement for single tooth replacement of either the left central incisor or the right canine in casts of the maxilla. Although there is usually good anatomic orientation in cases of single tooth replacement, variation in implant positions, angulations, and depth was reduced for implants that were placed using the navigation protocol. One might assume that in complex situations with less anatomic orientation, image guidance would be of greater advantage and could result in improvement of the functional and esthetic results and possible reduction of the surgical risk.[38,41,75]

Cost-Benefit Ratio

Computer aided implant surgery is more expensive than the standard technique and requires more effort, including CT imaging, fabrication of a registration template, and intraoperative referencing for bur tracking or image-guided manufacturing of a surgical template. The highest expenditures are associated with bur-tracking navigation systems, which cost about $60,000 to $200,000 US. During implant surgery, referencing and navigation add to the surgical time and may require ergonomic compromises for the surgeon's team, as the tracking elements on the registration template and the drill need constant visual contact to the stereotactic camera array.[61,75] An advantage is that such a system can be used for a wide range of craniomaxillofacial procedures (eg, image-guided biopsies, removal of foreign bodies, arthroscopy of the temporomandibular joint, osteotomies, distraction osteogenesis, and tumor surgery) and thus may represent a valuable acquisition for an institution.[76,77]

Compared to bur tracking, image-guided template production is less expensive and requires less effort, as there is no need for intraoperative referencing. In addition, outsourcing is possible with image-guided template production: the template can be fabricated by a remote company (eg, Med3D, Heidelberg, Germany, or SurgiGuide/Materialise Medical, Glen Burnie, MD), so that the oral surgeon or laboratory technician does not need to purchase expensive hardware.

As the implants are planned on the computer, familiarity with the system is needed for routine application. Specialized software optimized for dental implant surgery which is intuitive and easy to use can significantly reduce time and expenditure.[42,77]

Despite the expense, compared to the conventional technique, computer-aided implant surgery seems to be superior on account of its potential to eliminate possible manual placement errors and to systematize reproducible treatment success. The protection of critical anatomic structures and the esthetic and functional advantages of prosthodontic-driven implant positioning must also be considered.[20,37,42,77] Furthermore, the available bone can be fully utilized, which allows for longer implants (and thus superior implant stability) and perhaps the omission of additional surgical effort such as bone grafting or sinus augmentation.[38,41,78] Dental restorations with poor esthetics and functionality originating from suboptimal implant positioning may lead to discomfort and additional surgical effort, which means higher costs and a greater burden for the patient.

Considering these advantages, image guidance may have a positive cost/effort–benefit ratio, depending on the individual situation. With 12 years of clinical experience in computer-assisted navigation technology and 7 years in image-guided oral implant surgery, Ewers and associates[77] stated that "the application of this technology offers essential improvement in outcome and intraoperative safety" with a considerable technical expenditure (substantially depending on the software used). A further beneficial aspect of the use of computer-aided technology is the associated automatic and complete electronic documentation of the intervention.[42]

CONCLUSION

The accuracy of image-guided systems for oral implant surgery depends on all cumulative and interactive errors involved, from the data-set acquisition to the surgical procedure. A safety distance at least equivalent to the maximum deviation of the individual system is necessary. Similar accuracy data has been reported for bur tracking and image-guided template production, and both methods allow precise positioning of oral implants. Compared to the conventional technique, computer-aided implant surgery requires substantially greater investment and effort but seems to be superior on account of its potential to eliminate error and systematize reproducible treatment success. It also enables the protection of critical anatomic structures and the esthetic and functional advantages of prosthodontic-driven implant positioning. Based on clinical data, image guidance is not required for easy cases of sufficient anatomic orientation and bone height, but whenever a CT scan is recommended as a diagnostic means, when prosthodontic-driven implant positioning is to be precisely executed, and when safe positioning of implants with maximum length is desired for optimal use of the available bone, the patient can fully benefit from the advantages of complete 3D imaging, computer-aided planning, and image-guided surgery. Long-term clinical studies are necessary to examine all aspects of treatment success, to confirm the value of this strategy, and to justify the additional radiation dose, effort, and costs.

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