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Guided surgery: accuracy and efficacy

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Preoperative three-dimensional planning has gained popularity because of the introduction of cone beam computed tomography. Different concepts of three-dimensional planning, such as computer-guided (static) surgery and computer-navigated (dynamic) surgery, have been proposed to transfer virtual digital planning from a personal computer to the surgical field (42). In computer-guided (static) surgery, a static surgical guide is used that transfers the virtual implant position from computed tomography datato the surgical site. These guides are produced by computer-aided design/computer-assisted manufacture technologies, such as stereolithography, or manually in a dental laboratory, using mechanical positioning devices or drilling machines (42, 73, 78, 80). During computer-navigated surgery, the position of the surgical instruments in the surgical area is constantly displayed on a screen with a three-dimensional image of the patient. In this way, the system allows real-time transfer of the preoperative planning and visual feedback on the screen (16, 67, 82). In the review of Jung et al. (42), a statistically significant higher mean precision was found in favor of dynamic systems compared with the static surgical guides. However this difference could be explained by the fact that there are more preclinical studies on accuracy for the dynamic systems and more clinical studies for the static systems. In contrast to dynamic guidance, the 'static' guidance via surgical templates does not allow changes to be made to the surgical plan at the time of surgery. However, the bur sleeves of the templates permit rigidly guided and highly controllable drilling, which may be an advantage in areas where irregular bone is present. Furthermore, the intraoperative set-up of a navigation system is not required, and there are no time constraints and potential inconvenience of intraoperative registration and tracking. Intraoperative optical navigation devices are more frequently used in craniomaxillofacial surgery. Despite the fact that some clinical and accuracy studies are available, dynamic systems currently have a very limited indication in implant dentistry and are not in widespread use as a result of the initial high costs. Computer-navigated surgery systems are not included in the current review.

Using three-dimensional planning software, the surgeon can, after consulting with the dentist to provide a template representing the planned prosthesis, properly position implants in a virtual reality. When the planned prosthesis is incorporated into these computed tomography images, the planning can take into account both the jawbone anatomy and the planned superstructure. This should improve biomechanics and esthetics. Moreover, it may optimize the mutual interaction between the 'surgical' and the prosthetic teams. Precise preoperative planning has made it possible to implement immediate loading in a relatively predictive manner and hence reduce the treatment time and increase comfort for the patient. Furthermore, when combined with flapless surgery, it is presumed that postoperative patient morbidity and discomfort may also be reduced. As a result, implant placement may develop from difficult toward simple surgery and from stress toward relative comfort, for both the patient and the surgeon.

The limits of the use of static guided surgery are set by the maximum deviation observed between planning and postoperative outcome. Deviations may reflect the sum of all errors occurring from imaging to the transformation of data into a guide, to the improper positioning of the latter during surgery. Thus, all errors, although seldom occurring, can be cumulative. Much attention will be paid to the latter aspect. Indeed, when blind surgery is performed, as during a flapless approach, this is very relevant. Critical anatomical structures, such as the mandibular canal or mental foramen, must be avoided at all costs to

prevent neurological complications. The preoperative radiological determination of the distances between anatomical landmarks can lack precision (15), and this constitutes a serious risk, especially in the case of blind surgery. Significant variations can be observed within the systems working with surgical guides (e.g. for example, the guidance of the drills in the surgical templates). Some use different templates with sleeves with increasing diameter for one patient. Others apply removable sleeves in one single template (with removable sleeve inserts or sleeves on drills). Some systems have specially designed drills or drill stops to allow depth control, whereas others have indication lines on the drills. After preparation of the implant osteotomy, some systems allow guided placement of the implant, whereas for other systems the template has to be removed before implant insertion. These are only some examples illustrating how difficult it is to interpret and compare individual studies. The systematic reviews of Jung and co-workers (42) and Schneider and co-workers (67), who reviewed both accuracy and clinical efficacy, concluded that differing levels and quantity of evidence were available for computer-assisted implant placement and that future research should be directed to increase the number of clinical studies with longer observation periods and to improve the systems in terms of accuracy and efficacy.

This review aims to provide an overview of the accuracy of the procedure and also to give an overview of the efficacy of static guided surgery. The data from two recent systematic reviews (37, 73) are discussed in this paper.

Accuracy

Definition

Accuracy is defined as matching the position of the planned implant in the software with the actual position of the implant in the mouth of the patient. The accuracy of the implant or the osteotomy site is mostly expressed by four parameters (Fig. 1): deviation at the entry point; deviation at the apex; deviation of the long axis; and deviation in height/depth. Matching of the planned with the placed implant position can be based on a second (cone beam) computed tomography scan (allowing matching between preoperative planning and postoperative implant positions) or via 'model matching' (by comparing pre- and postoperative models of the treated jaw) (43). The mean deviations for model and computed tomography matching are quite similar: respectively,

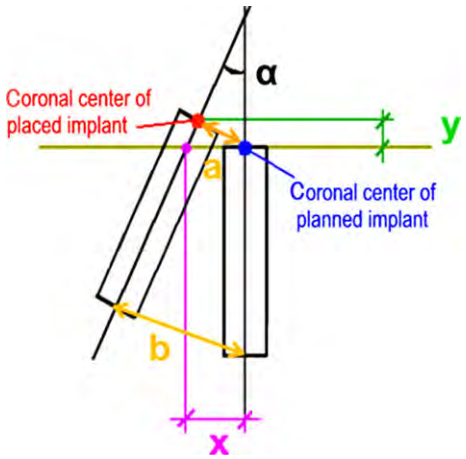

Fig. 1. Accuracy is expressed by the following parameters: a deviation at the entry point of the implant or cavity (indicated by letter a); deviation at the apex of the implant or cavity (indicated by the letter b); deviation of the axis of the cavity or implant (indicated by the symbol alpha); deviation in height/depth (indicated by the letter y) and the horizontal/lateral deviation (x).

0.5 (range: 0.1–1.2) mm and 0.8 (range: 0.1–2.7) mm at the entry point and 0.5 (range: 0.1–1.3) mm and 1.1 (range: 0.2–3.6) mm at the apex (46,59).

Findings

Data from a recent systematic review (73) revealed an overall mean deviation, at the entry point, of 1.0 mm (standard error = 0.12 mm; 95% confidence interval: 0.8–1.2); range: 0–6.5 mm. The corresponding data at the apex were 1.2 mm (standard error = 0.1 mm; 95% confidence interval: 1.0–1.6); range: 0–6.9 mm. The overall mean angulation was 3.8° (standard error = 0.3°, 95% confidence interval: 3.2–4.4); range: 0.0–24.9°. The overall mean vertical deviation (based on five studies) was 0.5 mm (standard error = 0.1 mm, 95% confidence interval: 0.2–0.7), with a maximum ranging from 2.3 to 4.2 mm. This review included 19 articles, which reported on accuracy. Of these studies, two were model based, five were on human cadavers and 12 were on patients. Four to 54 patients were included in each study, giving a total of 279 patients overall. The accuracy of 10 different static image-guided systems has been reported (Table 1). Large deviations were found to occur. The total deviation is the cumulative number of deviations that can occur at each step (80, 82). These deviations may be considered as very large, but an *in-vivo* randomized clinical trial comparing guided surgery with mental navigation (with or without any type of surgical template) is currently not available. Two *in-vitro* studies on acrylic models (53, 65) compared deviations for mental navigation with deviations for guided surgery, and a

Table 1. Comparison of the accuracy of 10 different static image-guided systems

Study	Study design	No. of implants	Site	Support	System	Template	No. of templates	Pins	Implant guided	Error entry (mm)		Error apex (mm)		Error angle (°)		Error depth (mm)	
										Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arisan et al. (6)	*In vivo*	279	Maxilla and mandible		Aytasarim Safe SurgiGuide	Stereolithography											
				Bone	Aytasarim Safe	Stereolithography	3	0	No	1.70	0.52	1.99	0.64	5.00	1.66		
				Bone	SurgiGuide	Stereolithography	3	0	No	1.56	0.25	1.86	0.40	4.73	1.28		
				Mucosa	Aytasarim Safe	Stereolithography	1	3	No	1.24	0.51	1.40	0.47	4.23	0.72		
				Mucosa	SurgiGuide	Stereolithography	1	3	Yes	0.70	0.13	0.76	0.15	2.90	0.39		
				Tooth involved	Aytasarim Safe	Stereolithography	1	0	No	1.31	0.59	1.62	0.54	3.50	1.38		
				Tooth involved	SurgiGuide	Stereolithography	1	0	Yes	0.81	0.33	1.01	0.40	3.39	0.84		
Behneke et al. (12)	*In vivo*	132	Maxilla and mandible	Tooth involved	Med3D	Laboratory	1	0	Sometimes	0.28		0.42		1.94			
		87	Maxilla							0.32		0.53		2.02			
		45	Mandible							0.32		0.42		2.25			
		24								0.21		0.28		1.49			
Cassetta et al. (18)	*In vivo*	227	Maxilla and mandible	Tooth involved, mucosa, bone		Stereolithography											
		116			SurgiGuide	Stereolithography	3	0	No	1.47	0.68	1.83	1.03	5.09	3.7	0.98	0.71
		57			Safe SurgiGuide	Stereolithography	1	Yes	Yes	1.49	0.63	1.9	0.83	3.93	2.34	0.85	0.63
		54			Safe SurgiGuide	Stereolithography	1	0	Yes	1.55	0.59	2.05	0.89	5.46	3.38	0.63	0.43
D'haese et al. (24)	*In vivo*	77	Maxilla	Mucosa	Facilitate	Stereolithography	1	> 4	Yes	0.91	0.44	1.13	0.52	2.60	1.61		
Di Giacomo et al. (25)	*In vivo*	21	Mandible and maxilla	Tooth involved, bone	SurgiGuide	Stereolithography	3	0	No	1.45	1.42	2.99	1.77	7.25	2.67		
Di Giacomo et al. (26)	*In vivo*	60	Maxilla and mandible	Mucosa	SinterStationHiQ	Stereolithography	1	2	No	1.35	0.65	1.79	1.01	6.53	4.31		
		22	Maxilla							1.51	0.62	1.86	1.07	8.54	4.2		
		38	Mandible							1.26	0.66	1.75	0.99	5.37	3.98		
Dreiseidler et al. (27)	*In vitro*	54	Maxilla and mandible	Tooth involved		Laboratory											
		24			NobelGuide		1	0	Yes	0.22	0.10	0.34	0.15	1.10	0.51	0.25	0.20
		30			SICAT		1	0		0.15	0.12	0.40	0.12	1.18	0.55		

Table 1. (*Continued*)

Study	Study design	No. of implants	Site	Support	System	Template	No. of templates	Pins	Implant guided	Error entry (mm)		Error apex (mm)		Error angle (°)		Error depth (mm)	
										Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ersoy et al. (29)	*In vivo*	94	Maxilla and mandible		Ay-Design	Stereolithography	> 1	Not applicable	No	1.22	0.85	1.51	1.00	4.90	2.36		
		23		Mucosa						1.10	0.70	1.70	1.00	4.90	2.20		
		45		Bone						1.30	1.00	1.60	1.50	5.10	2.70		
		26		Tooth involved						1.10	0.60	1.30	0.70	4.40	1.60		
		48	Maxilla							1.04	0.56	1.57	0.97	5.31	0.36		
		46	Mandible							1.42	1.05	1.44	1.03	4.44	0.31		
Ozan et al. (56)	*In vivo*	110	Maxilla and mandible	Tooth involved, mucosa, bone	Ay-Design	Stereolithography	> 1	0	No	1.10	0.70	1.41	0.90	4.10	2.30		
		58	Maxilla							0.95	0.50	1.41	1.00	4.85	2.40		
		52	Mandible							1.28	0.90	1.40	0.90	3.32	1.90		
		30		Tooth involved						0.87	0.40	0.95	0.60	2.91	1.30		
		50		Bone						1.28	0.90	1.57	0.90	4.63	2.60		
		30		Mucosa						1.06	0.60	1.60	1.00	4.51	2.10		
Pettersson et al. (58)	*Ex vivo*	145	Maxilla and mandible	Mucosa	NobelGuide	Stereolithography	1	3–5	Yes							0.39	0.59
		78	Maxilla							0.83	0.57	0.96	0.50	2.02	0.66		
		67	Mandible							1.05	0.47	1.24	0.58	2.46	0.67		
Pettersson et al. (59)	*In vivo*	139	Maxilla and mandible	Mucosa	NobelGuide	Stereolithography	1	Yes	Yes	0.80		1.09		2.26		−0.15	
		89	Maxilla							0.80		1.05		2.31		−0.06	
		50	Mandible							0.80		1.15		2.16		−0.29	
Ruppin et al. (62)	*Ex vivo*	~60	Mandible	Bone	SurgiGuide	Stereolithography	3	0	No	1.50	0.80	NA		7.90	5.00		
Sarment et al. (65)	*In vitro*	50	Mandible	Epoxy	SurgiGuide	Laboratory	3		Osteotomies	0.90	0.50	1.00	0.60	4.50	2.00		
Valente et al. (70)	*In vivo*	89	Maxilla and mandible	Tooth involved, mucosa, bone	SurgiGuide	Stereolithography	3	Not applicable	No	1.40	1.30	1.60	1.20	7.90	4.70	1.00	1.00

Table 1. (*Continued*)

Study	Study design	No. of implants	Site	Support	System	Template	No. of templates	Pins	Implant guided	Error entry (mm)		Error apex (mm)		Error angle (°)		Error depth (mm)	
										Mean	SD	Mean	SD	Mean	SD	Mean	SD
Van Assche et al. (71)	*Ex vivo*	12	Maxilla and mandible	Tooth involved	NobelGuide	Stereolithography	1	0 or 1	Yes	1.10	0.70	1.20	0.70	1.80	0.80		
Van Assche et al. (72)	*In vivo*	19	Maxilla and mandible	Tooth involved	NobelGuide	Stereolithography	1	0 or 1	Yes	0.60	0.30	0.90	0.40	2.20	1.10		
van Steenberghe et al. (76)	*Ex vivo*	10	Maxilla	Mucosa	NobelGuide	Stereolithography	1	0	Yes	0.80	0.30	0.90	0.30	1.80	1.00		
Vasak et al. (77)	*In vivo*	79	Maxilla and mandible	Tooth involved mucosa	NobelGuide	Stereolithography	1	Yes	Yes	0.46 BL 0.43 MD	0.35 BL, 0.32 MD	0.70 BL, 0.59 MD	0.49 BL, 0.44 MD	3.53	1.77	0.52	0.42
				Mucosa						0.49 BL, 0.46 MD		0.64 BL, 0.62 MD		3.50		0.60	
				Tooth involved						0.37 BL, 0.35 MD		0.88 BL, 0.49 MD		3.70		0.37	
			Maxilla							0.47 BL, 0.45 MD		0.70 BL, 0.59 MD		3.55		0.57	
			Mandible							0.41 BL, 0.36 MD		0.70 BL, 0.57 MD		3.68		0.34	
Widmann et al. (81)	*Ex vivo*	51	Maxilla and mandible	Three screws	Easy Taxis Aiming Device	Laboratory	1	3	Yes	1.10	0.60	1.20	0.70	2.80	2.10		

This table is adapted from the systematic review of Van Assche et al. (73). The first line of each study represents the overall data. If data are mentioned for subgroups. they are in the lines below. Pins, fixation pins; System, guiding system. BL, bucolingual; MD, mesiodistal.

significant improvement was observed in favor of guided surgery for all deviations. The angular deviations were 4.5° and 8.0° (65) in the first study and 4.2° and 10.4° in the second, for guided surgery and mental navigation, respectively (53). An *in-vivo* pilot study confirmed the higher accuracy of guided surgery (79).

Possible sources of error

Radiographic technique. Preoperative planning can be performed via multislice computed tomography or cone beam computed tomography (38, 39, 49, 57), with the latter offering imaging at low dose and relatively lower costs. Poeschl et al. (60) compared the accuracy of multislice computed tomography with that of cone beam computed tomography in image-guided surgery in an *in-vitro* model study. Acrylic mandibular models with four precise metal reference markers were scanned using multislice computed tomography and cone beam computed tomography. First of all, the distances between the fixed reference markers were measured using a three-axis drilling machine; then, they were measured for multislice computed tomography and cone beam computed tomography, applying different software systems. No statistically significant difference was found between multislice computed tomography and cone beam computed tomography. The difference between the mean value overall and the reference was 0.4 mm for multislice computed tomography and 0.5 mm for cone beam computed tomography. Arisan et al. (5) compared the accuracy of multislice computed tomography with that of cone beam computed tomography in a clinical study. Similar deviation values were found for multislice computed tomography and cone beam computed tomography: respectively, 0.8 (standard deviation = 0.3) mm and 0.8 (standard deviation = 0.3) mm at the entry point, 0.8 (standard deviation = 0.3) mm and 0.9 (standard deviation = 0.3) mm at the apex and 3.3 (standard deviation = 0.4)° and 3.5 (standard deviation = 0.4)° for angulation.

Patient's movement. The image quality of the (cone beam) computed tomography scan can impede the system's accuracy if motion or metal artifacts are present (27). Metal artifacts can result from metal-dense tooth restorations, and motion artifacts may result from patient movement (owing to lack of compliance or inappropriate fixation during the radiological investigation) (Fig. 2). Pettersson et al. (59) observed, during the matching procedure, that in some cases the segmented implants from the follow-up cone beam computed tomography scan were no longer cylindrical in shape. This could be explained by minor movements during scanning. Pettersson et al. (59) emphasized that such movements are not always visible on the three-dimensional images. Furthermore, the automatic superimposing procedure of gutta-percha markers (visible on the patient's cone beam computed tomography data and the prosthesis cone beam computed tomography data in the event that a dual scan had been performed) sometimes proceeded without any notification of errors. The 'movement' factor has a significant influence on the final accuracy. However, this statistically significant difference may not be clinically relevant.

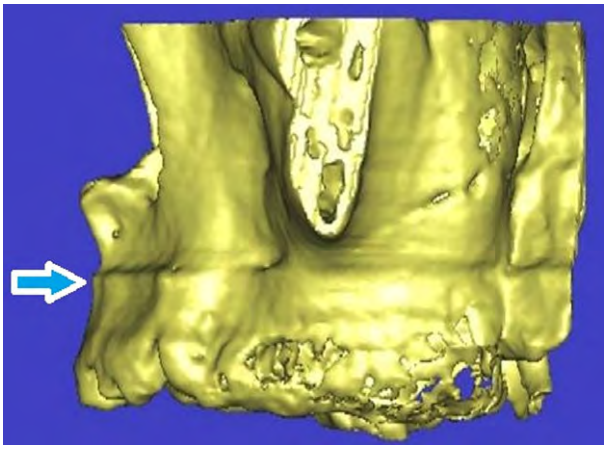

Fig. 2. Example of movement of the patient during the scan. The blue arrow on the three-dimensional model of the jaw shows a clear step, indicating that the patient has moved their head in a vertical manner.

Position of the scan prosthesis. The correct positioning of the scan prosthesis, in particular in cases where the scan prosthesis is transferred into the surgical guide, is extremely important. Therefore, an index is strongly recommended to position and stabilize the template in the mouth of the patient during the scanning process (Fig. 3). Optimal fit of the scan prosthesis with the patient's soft tissue is crucial. This can be controlled using the software to determine whether air is visible between the scan prosthesis and the soft tissues (Fig. 4A). If the scan prosthesis does not fit well, the following problems should be anticipated: incorrect position of the teeth in relation to the jawbone; incorrect planning of the implant positions; poor fit of the surgical guide, resulting in instability of the guide; and incorrect position of the surgical guide, resulting in inaccuracy. Furthermore, it is also important that the scan prosthesis has sufficient thickness (Fig. 4B).

Surgical guide production. The production of the surgical guide can be subdivided into two main

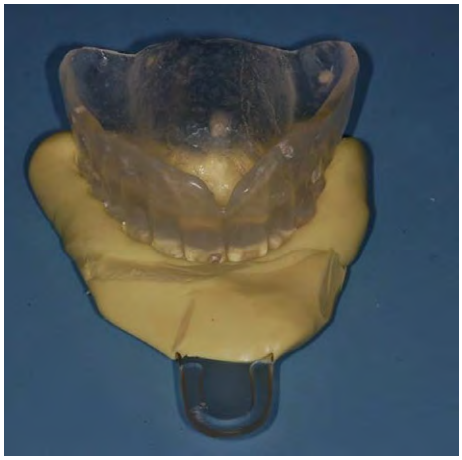

Fig. 3. Scan prosthesis with gutta-percha markers and index to stabilize the guide during the scanning procedure.

approaches: stereolithography; and laboratory production (for the latter the scan prosthesis is transferred into a surgical guide) (78). The overall deviation during the production of a stereolithographic guide is <0.25 mm (Fig. 5) (14, 64, 69). This deviation might occur during one of the following three steps: the (cone beam) computed tomography scan for acquisition of anatomical data of the patient; the image segmentation using dedicated software packages combined with data processing; and the building of the model itself, using one of several available rapid prototyping technologies (68). Production of the guide in the laboratory can be executed manually with the aid of a coordinate transfer apparatus or with the computer numerical control milling machine (11, 27, 28). The deviation of the latter is <0.5 mm (27). This overall deviation is also the sum of three steps: image quality of the (cone beam) computed tomography scan; the production of the scan prosthesis; and the production accuracy of the device, which transfers the planned implant positions to the corresponding drill sleeve positions in the scan prosthesis.

Positioning and stabilization of the surgical template. The positioning and stabilization of the surgical template can also influence the inaccuracy (Fig. 6A). This is even more so when several consecutive guides are used for drills with increasing diameter (2, 4). Arisan et al. (4) reported that their consecutive bone-supported guides frequently moved spontaneously away from the alveolar bone during drilling. This was seen especially in dense bone areas with a thin alveolar crest. However, even when one guide was used and fixed by fixation pins they occasionally found that fixation screws were loosened and required tightening. Therefore, one must check whether the guide remains stable in the correct position during the drilling process. Figure 6B shows an ideal distribution of fixation pins, with the distal pins behind the most posterior implant position. Furthermore, it is recommended that the most posterior pins are tightened before the anterior pins; because of the undercutting of the jaw in the front region, there is a risk of tilting the surgical guide when the anterior pins are tightened first. Another study (20) reported on a method to enhance the stabilization of the guide using a combination of bone–tooth supported guides. Via laser scanning, detailed dentition information was obtained, which is more accurate than the dentition information retrieved from the three-dimensional skull model reconstructed from computed tomography images. The laser-scanned dentition model was then superimposed on the computed tomography model, to serve as the basis for a more accurate three-dimensional model and resulting stereolithographic guide, which is supported by both tooth and bone. One publication (24) evaluated the interimplant deviation within a patient to investigate whether the deviation is related to malpositioning of the surgical guide or to individual malpositioning of the implants. They observed that the mean deviation was substantially different from the interimplant deviation (1.3 mm vs. 0.3 mm for apical inaccuracy). These results indicate that the inaccuracy is mainly determined by the mispositioning of the surgical guide. Future studies should look to both aspects.

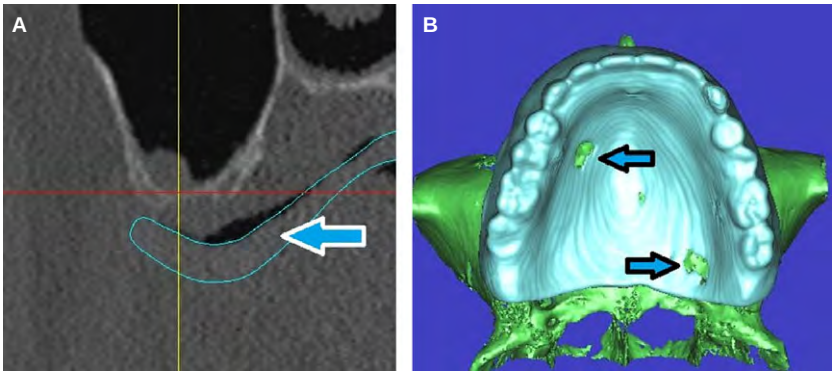

Fig. 4. (A) Cross-sectional image in the planning software. The blue arrow indicates the air between the radiographic guide and the mucosa. (B) Three-dimensional model of the jaw and the scan prosthesis. The blue arrows indicate insufficient thickness of the prosthesis.

Fig. 5. Example of a stereolithographic guide (courtesy of Materialise Dental®).

Tolerance of the drills. The tolerance of the drills within the drill guide and/or keys, as reported in two *in-vitro* studies (47, 74), underlines the importance of the position of the drill within the guide. The maximal deviation of the drill within the surgical guide can reach a maximum horizontal deviation of 1.3 mm at the implant shoulder and 2.4 mm at the apex for a 13-mm implant. A maximum deviation in angulation of 5.2° was observed (47). The latter is specific for each guiding system. This can also explain a deviation of the implants to the right for right-handed surgeons or to the mesial (especially for more distal implants). Data on these phenomena are limited. Di Giacomo et al. (26), as well as Vasak et al. (77), found significantly lower deviations for anterior implants compared with posterior implants. However, there are, of course, other explanations for this deviation. Horwitz et al. (36) observed that attrition of sleeves and drills, after longer use, are a contributing factor.

Mucosal thickness. The mucosal thickness (depending on the biotype or related to smoking) can influence the accuracy of mucosa-supported templates (23, 77). For example, the mean deviation at entry was 1.04 mm in thick mucosa (i.e. as seen in smokers) compared with 0.80 mm in thin mucosa (i.e. as seen in nonsmokers) (23). Another study (77) observed that an increase of 1 mm in the buccal mucosa thickness resulted in an increase of the buccolingual deviation of 0.41 mm.

Learning curve. The literature is not consistent on whether a learning curve is important; one clinical trial observed a learning curve (77), whereas two other studies did not (18, 70).

Jaw position. There is an inconsistency in the observations comparing the data of the maxilla with the mandible. Some publications reported no differences (6, 11, 26, 29), whereas others observed less deviation for the mandible (59, 77).

Computer-assisted implant system. Because of the heterogeneity in study designs included in the systematic review (73), comparison of different static computer-assisted implant systems (Ay-Design®, Aytasarim®, EasyTaxis®, SinterStationHiQ®, SurgiGuide®, Safe SurgiGuide®, SICAT®, Med3D®, NobelGuide® and Facilitate®) was impossible. Each guiding system has its advantages and disadvantages. More randomized studies are needed, using the same study design in a large population of patients, in order to calculate deviations for equivalent subgroups (same surgeon, same guiding device, same scanning procedure and same matching procedure).

Recommendations

To postulate recommendations for increasing accuracy, it is important to be aware that deviations reflect the sum of all errors occurring from imaging to the transformation of data into a guide, to the improper positioning of the latter during surgery. As a first step it is important to take a correct scan of an immobi-

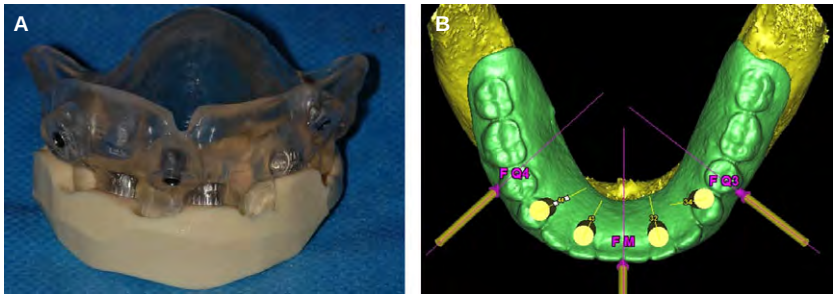

Fig. 6. (A) Example of a surgical guide with the surgical index, which will stabilize the guide during fixation on the underlying bone. (B) Implant planning in software. Three fixation screws are planned (and are well distributed); one at the midline and two posterior of the last implant position.

lized patient with an optimally fitted scan prosthesis. During the surgical procedure it is essential to place and fixate the surgical guide properly. For the latter it is strongly recommended to use fixation pins, and, if possible, to use one surgical guide in combination with sleeves of increasing internal diameter. During the drilling process, one has to be aware that a certain tolerance of the drills exists and that one has to check that the correct direction is followed during the entire drilling sequence. Concerning the computer-assisted implant systems, no recommendations can be given. In a randomized prospective study from our center (79) no difference could be found between two guiding systems (Materialise Universal® and Facilitate™) in patients edentulous in the maxilla or mandible.

Efficacy

Definition

To determine the efficacy of guided implant placement, the implant survival or success rate and the prosthesis survival rate following guided placement should be compared with that following conventional implant placement. Furthermore, different clinical protocols, such as flapless surgery, can also contribute to the efficacy of guided surgery.

Findings

Implant survival or success rate

Several studies presenting prospective observational data on the clinical performance of guided implant placement were identified (37). However, most of these studies had an observational period of <2 years (see Table 2) and only one study (63) had a follow-up period of up to 5 years. For these studies one can envisage survival rates comparable with those for conventional implant treatment. Also, lower success rates have been observed for smokers treated with guided surgery (3, 7, 8, 41). For example, a cohort study (63) reported cumulative survival rates of 81.2% and 98.9% for smokers and nonsmokers, respectively. The latter was confirmed in a prospective clinical study of D'haese et al. (22), in which patients were treated with flapless guided surgery in the maxilla (implant survival = 69.2% in smokers vs. 98.7% in nonsmokers).

Prosthesis survival rates

The prosthesis survival rates ranged widely (from 62% to 100%) (see Table 3), probably as a result of several factors – such as the definition of prosthesis survival, whether immediate or delayed loading was implemented and whether temporary or permanent prostheses were evaluated – and hence direct comparison with the conventional technique can be difficult. The computer-guided implant concept, in combination with immediate loading (Figs. 7A-D), is marketed as easy, safe and predictable. However, several complications or unexpected events were reported, as described in Table 2, as were fracture of the surgical guide (Fig. 8), dehiscences (31) and soft-tissue laceration (26). Misfit of the temporary prosthesis was the most common prosthetic complication, caused by inaccurate placement of the implants (Fig. 9A). After placement of the temporary prosthesis the most common complication was prosthesis fracture (Fig. 9B). It seems obvious that guided surgery, especially in combination with immediate loading, cannot be regarded as easier than conventional techniques.

Clinical protocol

Flapless surgery has gained interest since several articles showed that raising a flap leads to bone resorption (30, 34, 83). Via a flapless approach the periosteum and blood supply to the bone remain intact (10, 17) (Figs. 10A and 10B). Three studies compared guided flapless surgery with conventional open flap surgery and reported on patient-centered outcomes (4, 32, 55). These studies demonstrated a statistically significant reduction in immediate postoperative pain, use of analgesics, swelling, edema, hematoma, hemorrhage and trismus, for flapless surgery. One of these studies (4) also compared guided flapless surgery with guided open flap surgery and demonstrated a consistently better outcome for the flapless approach. These results are supported by the good scores for patient comfort and satisfaction reported by several observational studies on guided flapless surgery (1, 54, 75). A prolonged oral surgical intervention may increase postoperative pain and discomfort for the patient (66). One of the abovementioned controlled studies reported that the duration of the treatment with flapless guided surgery was less than half (24 min) of that needed for open flap guided surgery and/or conventional surgery (4). This observation is supported by Komiyama et al. (45) who reported that the duration of the flapless guided surgical intervention, including immediate reconstruction (Teeth-in-an-Hour concept; Nobel Biocare AB, Gothenburg, Sweden), took 30–45 min. Thus, the time factor may indeed be part of the explanation of why less pain and discomfort was reported by patients after flapless guided surgery. Even if the

Table 2. Prospective observational data on the clinical performance of guided implant placement

Study	Study design	Follow-up period (months)	System	Complications at guided implant placement			Complications after guided placement		
				Reason	No. of prosthetic events	Reason	No. of implant failures	No. of prosthetic events	Reason
Abad-Gallegos et al. (1)	Retrospective observational	Not reported	Nobel Guide	Lack of primary stablility. Limited oral aperture	Not reported	Lack of passive fit. Implant pain. Change to angulated abutment	10	Not reported	Screw loosening. Fracture of prosthesis or teeth
Arisan et al. (4)	Prospective comparative*	2–4	Aytasarim classic, Simplant-SAFE	Fracture of bone-supported surgical guides	Not applicable		5	Not applicable	
Barter (9)	Prospective observational	Mean = 49	coDiagnostiX and GonyX		Not reported		1	Not reported	
Berdougo et al. (13)	Retrospective comparative*	12–48	EasyGuide and CAD Implant system		Not reported		10	Not reported	
Cassetta et al. (19)	Retrospective observational	Not applicable	SimPlant Safe	Uncontrolled removal of gingiva. Alteration of external hexagon. Laceration. Template breakage. Limited implant stability	Not applicable		Not applicable	Not applicable	
Danza et al. (21)	Retrospective comparative*	1–41 (mean = 14)	Implant 3D and Ray-Set		Not reported		0	Not reported	
D´haese (22)	Prospective observational	12	Astra Facilitate	Misplacement owing to misfabrication of surgical guide	0		13	3	Esthetic reasons. Prosthesis fracture
Di Giacomo et al. (26)	Prospective observational	30	Implant Viewer 1.9 and Rhinoceros 4.0	Pulling of soft tissue. Insertion of wider implants than planned. Instability. Pain	1	Midline deviation	1	1	Prosthesis fracture
Fortin et al. (32)	Randomized control trial*	Not applicable	CAD implant system		Not reported		Not reported	Not reported	
Fortin et al. (33)	Prospective observational	48	EasyGuide	Implant lost before loading	Not applicable		0	Not reported	

Table 2. (*Continued*)

Study	Study design	Follow-up period (months)	System	Complications at guided implant placement			Complications after guided placement		
				Reason	No. of prosthetic events	Reason	No. of implant failures	No. of prosthetic events	Reason
Gillot et al. (35)	Prospective observational	12–51	Nobel Guide	Guide difficult to insert. Absence of primary stability	1	Major occlusal adjustment required for one patient	4	11	Fractures of resin. Prosthetic screw loosening
Johansson et al. (40)	Prospective observational	12	Nobel Guide	Misfit of occlusal index. Misfit of the surgical guide. Problems installing the implants	15	Problems getting the prosthesis in the exact position. Major occlusal adjustments	2	1	Prosthesis remade using standard abutments owing to difficulties in maintaining adequate oral hygiene
Katsoulis et al. (43)	Prospective comparative*	3	Nobel Guide		Not applicable		Not reported	Not reported	
Komiyama et al. (45)	Prospective observational	6–44 (mean ≥ 15)	Nobel Guide	Fracture of surgical template	8	Misfit of prosthesis. Major occlusal adjustments	19	Three prostheses	Prosthesis had to be removed owing to implant loss
Komiyama et al. (44)	Prospective observational	>12 (mean = 19)	Nobel Guide		Not applicable		Not applicable	Not applicable	
Lindeboom & van Wijk (48)	Randomized control trial	1	Nobel Guide		Not applicable		Not reported	Not reported	
Malo et al. (50)	Prospective observational	6–21 (mean = 13)	Nobel Guide		Not reported		2	10	
Meloni et al. (51)	Retrospective observational	18	Nobel Guide	Fracture of surgical template	2	Temporary prosthesis did not fit at time of placement	2	2	Fracture of the temporary prosthesis

Table 2. (*Continued*)

Study	Study design	Follow-up period (months)	System	Complications at guided implant placement			Complications after guided placement		
				Reason	No. of prosthetic events	Reason	No. of implant failures	No. of prosthetic events	Reason
Merli et al. (52)	Prospective observational	8	Nobel Guide	Fracture of surgical guide. Lost implant because primary stability could not be achieved	4	Prosthesis did not fit at time of placement	2	5	Fracture of temporary prosthesis. Prosthetic screw loosening. Fracture of porcelain coating of permanent prosthesis
Nikzad & Azari (54)	Prospective observational	12	Simplant, SurgiGuide		Not applicable		2	2	Fixtures lost. No seating of prosthesis
Nkenke et al. (55)	Prospective comparative*	12	NobelGuide		Not reported		0	Not reported	
Pomares (61)	Retrospective observational	12	NobelGuide	Fracture of surgical template	3	Misfit of temporary prosthesis	4	8	Fracture of temporary prosthesis
Sanna et al. (63)	Prospective observational	6–60 (mean = 26)	NobelGuide		Not reported		9	Not reported	
van Steenberghe et al. (75)	Prospective observational	12	NobelGuide		2	Prosthetic misfit. Midline deviation	0	3	Occlusal material fracture. Prosthetic screw loosening
Yong & Moy (84)	Prospective observational	Mean = 27	NobelGuide	Too deep placement of one implant which was removed (failure)	2	Incomplete seating of prosthesis owing to bony interference	7	12	Speech problem. Bilateral cheekbiting. Fracture of prosthesis. Heavy occlusal wear. Screw loosening

This table was adapted from the systematic review of Hultin & Svensson (37)
*Control group included conventional open flap surgery.

Table 3. Prosthesis survival rates

Study	Survival rate							Other outcome
	Immediate/Delayed loading		Implants		Prosthesis		Follow-up period (months)	
	With guided placement	Without guided placement	With guided placement (%)	Without guided placement	With guided placement (%)	Without guided placement		
Barter (9)	Not reported	Not reported	98	Not applicable	100	Not applicable	Mean = 49	
Berdougo et al. (13)*	Not reported	Not reported	96	99%	Not reported	Not reported	12–48	
Danza et al. (21)*	Immediate loading/ Delayed loading	Immediate loading/ Delayed loading	100	96%	Not reported	Not reported	1–41 (mean = 14)	
D'haese et al. (22)	Immediate loading/ Delayed loading	Not applicable	89	Not applicable	62†	Not applicable	12	99% implant survival rate in nonsmokers and 74% in smokers. Smoking and immediate loading in combination in edentulous maxillae increased implant loss
Di Giacomo et al. (26)	Immediate loading	Not applicable	96	Not applicable	92	Not applicable	30	
Fortin et al. (33)	Delayed loading	Not applicable	98	Not applicable	Not reported	Not applicable	48	
Gillot et al. (35)	Immediate loading	Not applicable	98	Not applicable	100	Not applicable	12–51	Removal and replacement of adjustable abutments used in the temporary prosthesis was unpleasant for the patients
Johansson et al. (40)	Immediate loading	Not applicable	99	Not applicable	96	Not applicable	12	Mean marginal bone loss of 1.3 mm; 19% of the subjects had > 2 mm bone loss; mucosal inflammation was present in 23% of probed sites
Komiyama et al. (45)	Immediate loading	Not applicable	89	Not applicable	84	Not applicable	6–44 (mean ≥ 15)	Bleeding on probing = 82% (16–100%). Bone loss was more common when pressure-like mucosal ulcers were detected under the prosthesis

Table 3. (*Continued*)

Study	Survival rate							Other outcome
	Immediate/Delayed loading		Implants		Prosthesis		Follow-up period (months)	
	With guided placement	Without guided placement	With guided placement (%)	Without guided placement	With guided placement (%)	Without guided placement		
Malo et al. (50)	Immediate loading	Not applicable	98	Not applicable	Not reported	Not applicable	6–21 (mean = 13)	21% of all measured sites at 6 months and 28% at 12 months had > 2 mm radiographic bone loss
Meloni et al. (51)	Immediate loading	Not applicable	98	Not applicable	87‡	Not applicable	18	Mean marginal bone loss of 1.6 mm after 18 months
Nikzad et al. (54)	Delayed loading	Not applicable	96	Not applicable	Not reported	Not applicable	12	Mean pain score on visual analog scale at follow-up was within the range for little or no pain
Nkenke et al. (55)*	Immediate loading	Immediate loading	100	100%	100	100%	12	Guided surgery generated less postoperative pain and swelling compared with open flap surgery
Pomares (61)	Immediate loading	Not applicable	98	Not applicable	100	Not applicable	12	
Sanna et al. (63)	Immediate loading	Not applicable	95	Not applicable	Not reported	Not applicable	6–60 (mean = 26)	Mean marginal bone loss of 2.6 mm in smokers and 1.2 mm in nonsmokers
van Steenberghe et al. (75)	Immediate loading	Not applicable	100	Not applicable	100	Not applicable	12	Mean marginal bone loss of 1.2 mm mesial and 1.1 mm distal
Yong and Moy (84)	Immediate loading	Not applicable	91	Not applicable	Not reported	Not applicable	Mean = 27	

Outcome was determined in studies using static guided systems and with a mean follow-up of ≥ 12 months. This table was adapted from the systematic review of Hultin and Svensson (37).
*Control group included conventional open flap surgery.
†Survival rate reported on temporary prosthesis for the immediately loaded cases.
‡Survival rate reported on temporary prostheses.

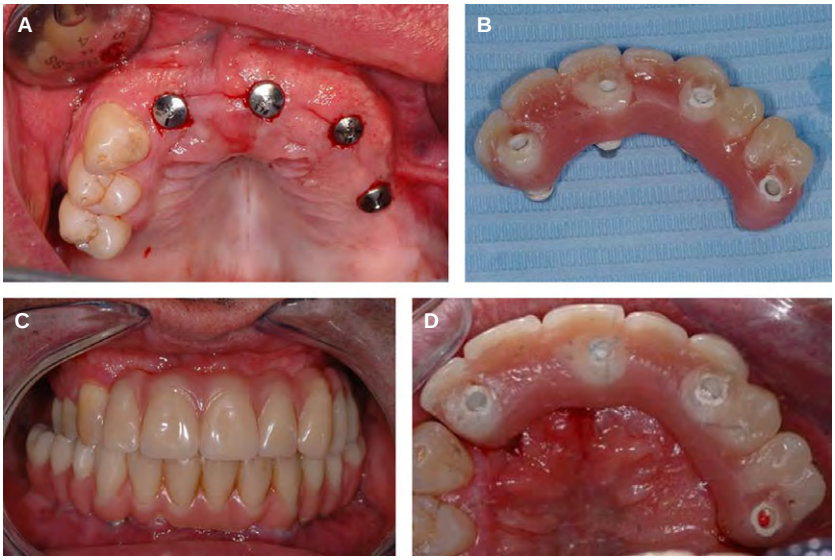

Fig. 7. (A–D) Clinical case of a patient treated with flapless guided surgery and immediately restored with a temporary partial bridge.

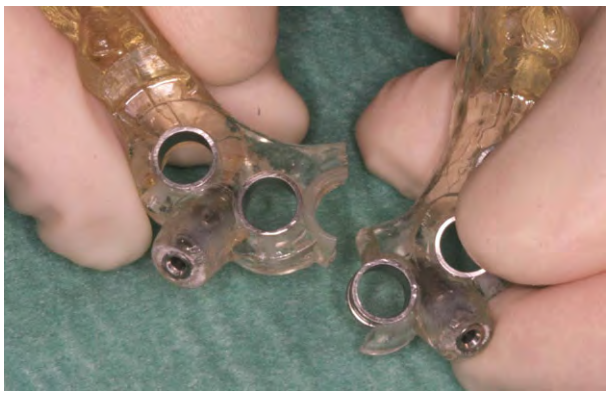

Fig. 8. Example of a fracture of the surgical guide (courtesy of Prof. Björn Klinge).

duration of the surgical intervention is shorter with flapless guided surgery compared with conventional techniques, it seems that much more time has to be invested in the preoperative planning. The flapless guided implant placement technique allows the surgeon to install the implants with minimal surgical trauma to the bone and associated soft tissues. As such, these techniques may be particularly attractive for use in frail patients. However, again, very limited information is available. Horwitz et al. (36) described the use of flapless guided implant placement in an irradiated cancer patient and showed good results after 2 years. In the study by Barter (9), six patients were treated with flapless guided surgery to avoid secondary exposure of previously grafted sites. The implant survival rate was 98% and all prostheses were still in use after 4 years.

Cost effectiveness

The cost effectiveness of different guided surgery protocols is difficult to judge as no information on this parameter could be found in the scientific literature. An interesting clinical question is whether these techniques can be used as an alternative to bone augmentation. Unfortunately, only one article addresses this question. Fortin et al. (33) used the guided technique in partially edentulous patients with severely resorbed maxillae and reported a 98% implant survival rate after 4 years.

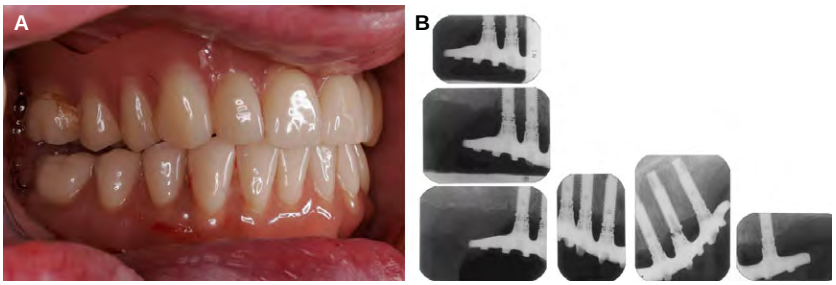

Fig. 9. (A) Misfit of the prefabricated prosthesis. (B) Radiographs showing the misfit of the prefabricated prosthesis.

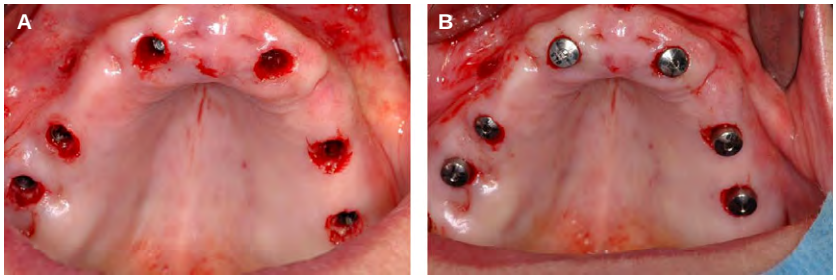

Fig. 10. Clinical picture of flapless surgery in the maxilla after removal of the guide (A) and after placement of the abutments (B).

Conclusion

Different computer-assisted implant placement procedures are currently available. They differ in software, template manufacture, guiding device, stabilization and fixation. The literature seems to indicate that one has to accept a certain inaccuracy of ±2.0 mm, which seems large initially but is clearly less than for nonguided surgery. A reduction of the accuracy to below 0.5 mm seems extremely difficult. A common shortcoming identified in the studies included for this review was inconsistency in how clinical data and outcome variables were reported. Another limitation was the small number of comparative clinical studies. In order to find the best guiding system/most important parameters for optimal accuracy, more randomized clinical trials, which also include information on cost-effectiveness, patient-centered evaluations (i.e. questionnaires and interviews) and longer follow-up periods are necessary. Future research should consider the use of flapless guided implant placement in special subgroups of patients (for example those with severely resorbed jaws and osteoporosis, and those treated with radiotherapy).

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