CLINICAL ORAL IMPLANTS RESEARCH

N. Van Assche
M. Vercruyssen
W. Coucke
W. Teughels
R. Jacobs
M. Quirynen

Accuracy of computer-aided implant placement

Authors' affiliations:
N. Van Assche, M. Vercruyssen, W. Teughels, M. Quirynen, Department of Periodontology, Catholic University Leuven, Kapucijnenvoer, 33, 3000, Leuven, Belgium
W. Coucke, Department of Quality of Medical Laboratories, Scientific Institute of Public Health, J. Wytsmanstraat 14, 1050, Brussel, Belgium
R. Jacobs, Oral Imaging Center, Catholic University Leuven, Kapucijnenvoer, 33, 3000, Leuven, Belgium

Corresponding author:
N. Van Assche
Department of Periodontology, Faculty of Medicine KU Leuven, Kapucijnenvoer 33, B-3000 Leuven, Belgium
Tel.:+32 14 59 49 99
e-mail: nele_van_assche@hotmail.com

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Abstract

Aim: To assess the accuracy of static computer-guided implant placement.

Material and methods: Electronic and manual literature searches were conducted to collect information on the accuracy of static computer-guided implant placement and meta-regression analyses were performed to summarize and analyse the overall accuracy. The latter included a search for correlations between factors such as: support (teeth/mucosa/bone), number of templates, use of fixation pins, jaw, template production, guiding system, guided implant placement.

Results: Nineteen accuracy studies met the inclusion criteria. Meta analysis revealed a mean error of 0.99 mm (ranging from 0 to 6.5 mm) at the entry point and of 1.24 mm (ranging from 0 to 6.9 mm) at the apex. The mean angular deviation was 3.81° (ranging from 0 to 24.9°). Significant differences for all deviation parameters was found for implant-guided placement compared to placement without guidance. Number of templates used was significant, influencing the apical and angular deviation in favour for the single template. Study design and jaw location had no significant effect. Less deviation was found when more fixation pins were used (significant for entry).

Conclusion: Computer-guided implant placement can be accurate, but significant deviations have to be taken into account. Randomized studies are needed to analyse the impact of individual parameters in order to allow optimization of this technique. Moreover, a clear overview on indications and benefits would help the clinicians to find the right candidates.

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During the last decade, special attention was given to a "prosthesis driven" implant placement, to optimize the aesthetic outcome of the final restoration with optimal loading conditions and good access for cleaning. Three-dimensional imaging (showing the alveolar bone in relation to the ideal tooth position), obtainable with relative low radiation dosages especially when cbCT are used (Loubele et al. 2009; Pauwels et al. 2012) in combination with planning software opened the possibility for preoperative planning and proper communication among the patient, the surgeon and the prosthodontist. During the last few years different strategies have been developed to transfer the digitally planned implant positions to the patient. Today, some clinicians favour guided implant insertion whereas others still have doubts about their usefulness and especially their accuracy.

The protocol involves several steps including a radiographic template, scanning procedure, planning, and surgery (with or without a surgical template). The accuracy at the end is the overall deviation from the start until placement of the implants. Mistakes can occur at each individual step and can accumulate. Therefore, it is crucial to understand the significance of each step, and especially to realize the magnitude of the cumulated inaccuracy. The latter is important not only to prevent damage of vital structures, but also to keep the implants within the bony envelop and especially to prevent adverse events.

Different concepts have been proposed to transfer the virtual digital planning to the surgical field. Computer-guided (static) surgery or computer-navigated (dynamic) surgery (Jung et al. 2009). For computer-guided surgery a static surgical guide is used, that reproduces the virtual implant position from computerized tomographic data. These guides are produced by computer-aided design/computer-assisted manufacture(CAD/CAM) technology, such as stereolithography or manually in a dental laboratory (using mechanical positioning devices or drilling machines) (van Steenberghe et al. 2005; Vercruyssen et al. 2008).

With computer-navigated surgery the current position of the surgical instruments in the surgical area is constantly displayed on a screen with a 3D image of the patient. In this way, the system allows real-time transfer of the preoperative planning and visual feedback on the screen (Widmann and Bale 2006; Brief et al. 2005). In the review of Jung and co-workers, a statistically significant higher mean precision was found in favour of dynamic systems compared with the static surgical guides. However, this difference could be explained by the fact that there were more preclinical studies on accuracy for the dynamic systems and more clinical studies for the static systems. The computer-navigated surgery systems were not included in the current systematic review.

Within the systems working with surgical guides significant variations can be observed (e.g. for example the guidance of the drills in the surgical templates). Some use for one patient different templates with sleeves with increasing diameter, others apply removable sleeves in one single template (with removable sleeve inserts or sleeve on drills). Some systems design special drills or drill stops to allow depth control whereas others have indication lines on the drills. After the preparation of the implant osteotomy, other systems allow a guided placement of the implant whereas for other systems the template has to be removed before implant insertion.

These are only some examples to illustrate how difficult it is to interpret and compare individual studies. This systematic review aims to summarize the available data on the accuracy of computer-guided implant placement, and will try to find some limitations/indications. It is an update of the systematic review from Jung et al. (2009) and Schneider et al. (2009), who besides the accuracy, also reviewed the clinical outcome. They also reported on the per-operative complications (e.g. too limited inter-occlusal distance, lack of primary stability of implants, need for grafting).

Patients related outcome variables (e.g. pain, swelling, discomfort, postoperative bleeding etc.) as well as socio-economic aspects (costs, number of consultations, duration of treatment, etc.) are also essential, but data on these topics are scarce and were not included in this review.

Material and methods

An electronic literature search of the PubMed database was performed with the intention of collecting relevant information on accuracy of computer-aided implant placement. The search included articles published from 1996 up to December 2011. It was limited to English, German, Italian or French papers. Following search terms were used: *dental* or *oral*, *implant**, *guid** and *compute**. Two reviewers (NVA, MV) reviewed all the titles, abstracts and papers, independently. Every search was complemented by manual searches of the reference list of all selected full text articles. In addition, full text copies of review articles published between January 2004 and December 2011 were explored (Fig. 1).

Inclusion/exclusion criteria

Clinical, preclinical and *ex vivo* studies were included if data were available on the amount and direction of implant or instrument deviation. Studies with zygoma or pterygoid implants, or mini-implants for orthodontic purposes were excluded. Reviews were not included for data analysis.

Data extraction

Two reviewers extracted independently the data using data extraction tables. Any disagreements were solved by discussion. Data were only included if there was agreement between the two reviewers.

Outcome variables

The following four parameters were evaluated (Fig. 2):

1. deviation at the entry point of the implant or cavity
2. deviation at the apex of the implant or cavity
3. deviation of the axis of the cavity or implant
4. deviation in height/depth.

Parameters 1 and 2 can each be reported by one distance, or by two individual vectors (with a horizontal (x) and a vertical (y) distance).

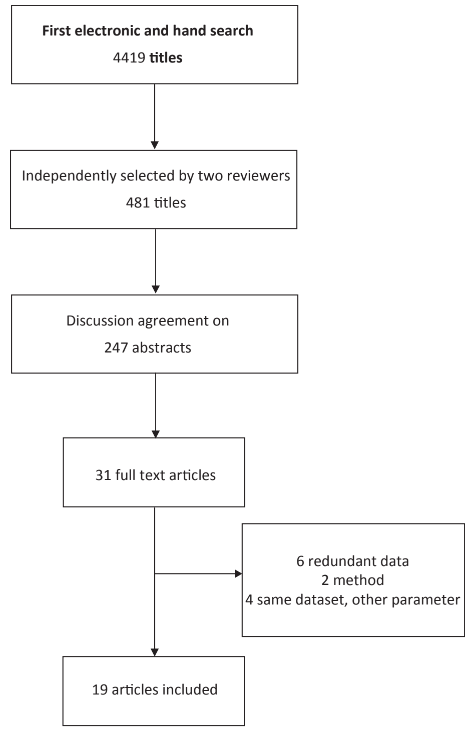

Fig. 1. Evolution of electronic literature search and selection of articles.

Statistical analysis

Methods appropriate for meta analysis of the mean values and their corresponding standard errors observed in groups of a given size were used. When unavailable, standard errors were derived from the standard deviations (standard deviation divided by the square root of the number of data). In case standard deviations were unavailable, they were calculated by dividing the range by 4.

Heterogeneity between studies was assessed with the I^2 statistic as a measure of the proportion of total variation in estimates that is due to heterogeneity and it was decided to use random models. The influence of study design, support, number of templates, use of fixation pins, jaw, template production, guiding system, guided implant placement was assessed for the four parameters by means of meta-regression.

Summary estimates and 95% confidential intervals (95% CI) and *P*-values from meta-regression for assessing differences in outcomes between groups of studies are reported and displayed in Forest plots. All analyses were done using R2.14.

Results

The evolution of the electronic search is summarized in Fig. 1. After initial identification of

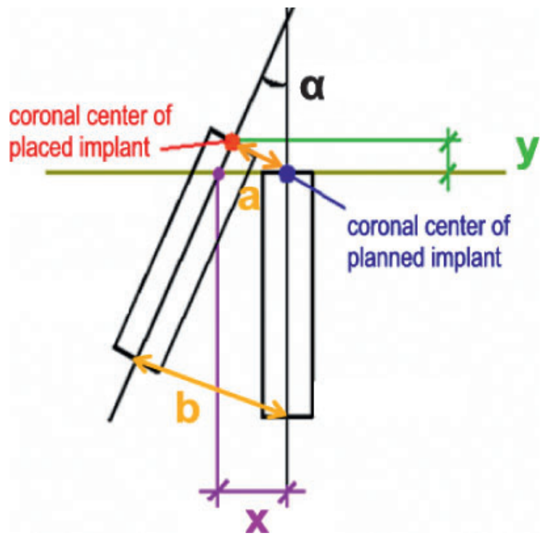

Fig. 2. Parameters used to analyse the accuracy of the implant placement, by matching the soft-ware planned implant position, with the final position of the implant in patients' jawbone. Following abbreviations were used: a = deviation at entry b = deviation at apex x= horizontal deviation y= vertical deviation α= apical deviation

titles ($n_{oral\ implant^*\ compute^*}$= 170, $n_{oral\ implant^*\ guid^*}$= 141, $n_{dental\ implant^*\ compute^*}$= 2278, $n_{dental\ implant^*\ guide^*}$= 1828) and hand search (2 articles), the exclusion of irrelevant studies was performed by two independent reviewers (NVA, MV), who reduced the numbers of titles to ($n_{oral\ implant^*\ compute^*}$= 17, $n_{oral\ implant^*\ guid^*}$= 16, $n_{dental\ implant^*\ compute^*}$= 129, $n_{dental\ implant^*\ guide^*}$= 85). After review of these manuscripts' abstracts, 31 publications were selected for full text evaluation. From these, 12 studies were withdrawn the reasons mentioned in Table 1.

Thus, a total of 19 accuracy studies were ultimately used for this review (Fig. 1, Table 2a–c).

Material

From the 19 included data sets, 2 were on models, 5 on human cadavers and 12 in patients.

The range of included patients was 4–54, with a total of 279 patients. Three papers reported only on full edentulous patients, although most articles (*n* = 9) also included partial cases.

Systems

Ten different "static" computer-assisted implant systems were used (Ay-Design®, Aytasarim®, EasyTaxis®, SinterStationHiQ®, SurgiGuide®, Safe SurgiGuide®, SICAT®, Med3D®, NobelGuide®, Facilitate®) in the included studies. The number of respective studies reporting these systems (any study design) is very variable, ranging from 1 (Ay-Design®, Aytasarim®, EasyTaxis®, SinterStationHiQ®, SICAT®, Med3D®, Facilitate®) to 7 (NobelGuide®).

Drillings/Implants/Positions and their evaluations

A total of 1688 implant positions were matched to the preoperative planning, with 1326 *in vivo*, 104 *in vitro* (boreholes and implant positions), and 218 *ex vivo* in human cadavers. In the *in vitro* study of Ruppin et al. (2008) the number of inserted implants was unfortunately not mentioned.

The matching between planned and placed implant position was always based on a second (cone beam)CT allowing a fusion between preoperative planning and postoperative implant positions. The applied parameters are highlighted in Fig. 2. Behneke and co-workers (Behneke et al.2011a, 2011b), and Dreiseidler et al. (2009) and Widmann et al. (2010) measured a horizontal and vertical component at entry and/or apex. All the other studies reported only one distance for this deviation (the distance between centre of planned and placed implant).

The overall mean deviation at the entry point was 0.99 mm (SE 0.12 mm, 95% CI 0.75 – 1.22), ranging from 0 mm to 6.5 mm. The corresponding data at the apex were 1.24 mm (SE 0.13 mm, 95% CI 1.01 – 1.56), ranging from 0 mm to 6.9 mm. The overall mean angulation was 3.81° (SE 0.32°, 95% CI 3.18 – 4.43), ranging from 0.00° to 24.9°. The overall mean vertical deviation (based on five studies) was 0.46 mm (SE 0.14, 95% CI 0.20 – 0.72), ranging from -2.33 to 4.2 mm.

The extracted data allowed further statistical analysis for support, number of templates, use of fixation pins, jaw, template production and guided implant placement. The data for error at entry, error at apex and angulation for *in vivo* studies are presented in Table 3a. This table gives an overview of the mean, standard error (SE) and 95% confidence interval (95% CI) for a specific subgroup, without taking into account interactions of other possible parameters. These values are based on the mentioned number of studies (nStud) and number of implants (nI).The *P* value (in bold) gives the result of the statistical comparison.

It was not possible to mention "the" minimal and maximal among all studies for each deviation and subgroup. Unfortunately, minimum and maximum values were not always mentioned.

Table 1. **Reason for exclusion**

Article	Reason for exclusion
Al Harbi & Sun 2009	Method (Matching procedure was unclear, placed implant served as control),),
Barnea et al. 2010	Redundant data
Behneke et al. 2012	Same data set Behneke et al. 2011, data Behneke et al. 2011 more detailed information for this review
Cassetta et al. 2011b	Same dataset as Cassetta et al. 2011b. Data Cassetta et al. 2011a contains more detailed information for this review
Chen et al. 2010	Method (two different systems were used, unclear description)
D'haese and De Bruyn 2011	Same data set of 2009, (influence of mucosal thickness/smoking habits on accuracy).
Eggers et al. 2009	Redundant data (five same templates, two surgeons)
Fortin et al. 2003	Redundant data (report on clinical outcome (complications))
Horwitz et al. 2009	Redundant data (study to assess accuracy of matching procedure)
Kalt & Gehrke 2008	Redundant data
Komiyama et al. 2011	Same data set Pettersson 2010a, model based matching, data Pettersson were used because most compatible with other studies to compare (CT-matching)
Nickenig et al. 2010	Redundant data (reports on clinical outcome)

Table 2a. **Descriptive table of *in vivo* studies**

nArt	nS	nI	site	support	guide system	Templ	nTempl	Pins	impl guided	error entry (mm) mean	SD	min	max	error apex (mm) mean	SD	min	max	error angle (°) mean	SD	min	max	error depth (mm) mean	SD	min	max
1	54	279	max & mand		Ayt, Safe S	SLA																			
				B	Ayt	SLA	3	0	no	1.7	0.52	1.2	3.48	1.99	0.64	1.18	3.8	5	1.66	1.2	8.2				
				B	Safe S	SLA	3	0	no	1.56	0.25	1.1	2.1	1.86	0.4	1.44	2.6	4.73	1.28	2,9	6.9				
				M	Ayt	SLA	1	3	no	1.24	0.51	0.5	2.7	1.4	0.47	0.8	2.83	4.23	0.72	2.1	6				
				M	Safe S	SLA	1	3	yes	0.7	0.13	0.2	0.83	0.76	0.15	0.4	0.99	2.9	0.39	0.8	3.5				
				T	Ayt	SLA	1	0	no	1.31	0.59	0.6	2.9	1.62	0.54	0.78	3.4	3.5	1.38	0.9	5.9				
				T	Safe S	SLA	1	0	yes	0.81	0.33	0.33	1.6	1.01	0.4	0.29	1.72	3.39	0.84	1.4	4.6				
2	52	132	max & mand	T	Med3D	L	1	0	sometimes	0.28		0.01	0.97	0.42		0.03	1.38	1.94		0.07	6.26				
		87	max							0.32		0.03	0.92	0.53		0.03	1.38	2.02		0.14	6.26				
		45	mand							0.32		0.01	0.97	0.42		0.03	1.15	2.25		0.07	5.82				
		24								0.21		0.03	0.6	0.28		0.03	0.77	1.49		0.07	4.53				
3	20	227	max & mand	T, M, B		SLA																			
	10	116			Surg	SLA	3	0	no	1.47	0.68	0.17	3.88	1.83	1.03	0.07	6.41	5.09	3.7	0.2	21.16	0.98	0.71	0.02	3.53
	10	57			Safe S	SLA	1	yes	yes	1.49	0.63	0.13	3	1.9	0.83	0.44	3.98	3.93	2.34	0.28	14.34	0.85	0.63	0.03	2.29
		54			Safe S	SLA	1	0	yes	1.55	0.59	0.13	2.79	2.05	0.89	0.34	4.23	5.46	3.38	0.1	15.25	0.63	0.43	0.05	1.58
4	13	77	max	M	Fac	SLA	1	>4	yes	0.91	0.44	0.29	2.45	1.13	0.52	0.32	3.01	2.6	1.61	0.16	8.86				
5	4	21	mand & max	T, B	Surg	SLA	3	0	no	1.45	1.42			2.99	1.77			7.25	2.67						
6	12	60	max & mand	M	Sin	SLA	1	2	no	1.35	0.65	0.09	2.69	1.79	1.01	0.11	4	6.53	4.31	0.04	18.64				
		22	max							1.51	0.62			1.86	1.07			8.54	4.2						
		38	mand							1.26	0.66			1.75	0.99			5.37	3.98						
7	21	94	max & mand		Ay-D	SLA	>1	NA	no	1.22	0.85			1.51	1			4.9	2.36						
		23		M						1.1	0.7			1.7	1			4.9	2.2						
		45		B						1.3	1			1.6	1.5			5.1	2.7						
		26		T						1.1	0.6			1.3	0.7			4.4	1.6						
		48	max							1.04	0.56			1.57	0.97			5.31	0.36						
		46	mand							1.42	1.05			1.44	1.03			4.44	0.31						
8	30	110	max & mand	T, M, B	Ay-D	SLA	>1	0	no	1.1	0.7			1.41	0.9			4.1	2.3						
		58	max							0.95	0.5			1.41	1			4.85	2.4						
		52	mand							1.28	0.9			1.4	0.9			3.32	1.9						
		30		T						0.87	0.4			0.95	0.6			2.91	1.3						
		50		B						1.28	0.9			1.57	0.9			4.63	2.6						
		30		M						1.06	0.6			1.6	1			4.51	2.1						
9	23	139	max and mand	M	Nob	SLA	1	yes	yes	0.8		0.1	2.68	1.09		0.24	3.62	2.26		0.24	11.74	−0.15		−2.33	2.05
		89	max							0.8		0.1	2.68	1.05		0.25	2.63	2.31		0.24	6.96	−0.06		−1.65	2.05
		50	mand							0.8		0.1	2.45	1.15		0.24	3.62	2.16		0.27	11.74	−0.29		2.33	0.94
10	25	89	max & mand	T, M, B	Surg	SLA	3	NA	no	1.4	1.3	0.2	6.5	1.6	1.2	0	6.9	7.9	4.7	0.7	24.9	1	1	0	4.2
11	18	79	max & mand	T, M	Nob	SLA	1	yes	yes	0.46 BL, 0.43 MD	0.35 BL, 0.32 MD		1.42 BL, 1.5 MD	0.7 BL, 0.59 MD	0.49 BL, 0.44 MD		1.84 BL, 1.89 MD	3.53	1.77		8.1	0.52	0.42		2.02
				M						0.49 BL, 0.46 MD				0.64 BL, 0.62 MD				3.5				0.6			

Table 2a. (continued)

nArt	nS	nI	site	support	guide system	Templ	nTempl	Pins	impl guided	error entry (mm) mean	SD	min	max	error apex (mm) mean	SD	min	max	error angle (°) mean	SD	min	max	error depth (mm) mean	SD	min	max
				T						0.37 BL, 0.35 MD				0.88 BL, 0.49 MD				3.7				0.37			
			max							0.47 BL, 0.45 MD				0.70 BL, 0.59 MD				3.55				0.57			
			mand							0.41 BL, 0.36 MD				0.70 BL, 0.57 MD				3.68				0.34			
12	7	19	max & mand	T	Nob	SLA	1	0 or 1	yes	0.6	0.3	0.1	1.4	0.9	0.4	0.2	1.8	2.2	1.1	0.5	3.9				

Legend: First line of each study represents overall data, if data mentioned for subgroups, they are in lines below. nArt= number article, nS= number of patients, nI=number of implants, Guide: SLA= stereolithography, L=laboratory, Support: T=tooth involved, M=mucosa, B=bone, Templ= surgical template, nTempl= number of surgical templates, Pins= fixation pins, Ay-D= Ay-Design, Ayt= Aytasarim, Fac= Facilitate, Sim= Simplant, Surg = SurgiGuide, Safe S= Safe SurgiGuide, Nob=NobelGuide, Sin= SinterStationHiQ.
Number of study: 1=Arisan et al. (2010), 2= Behneke et al. (2011), 3= Cassetta et al. (2011a), 4= D′haese et al. (2009), 5= Di Giacomo et al. (2005), 6= Di Giacomo et al. (2011), 7= Ersoy et al. (2008), 8= Ozan et al. (2007), 9= Pettersson et al. (2010a), 10= Valente et al. (2009), 11= Vasak et al. (2011), 12= Van Assche et al. (2010).

Table 2b. **Descriptive table for *in vitro* studies**

Art	nS	nI	site	support	guid system	Templ	nTempl	Pins	impl guided	error entry (mm) mean	SD	min	max	error apex (mm) mean	SD	min	max	error angle (°) mean	SD	min	max	error depth (mm) mean	SD	min	max
1	10	54	max & mand	T		L																			
		24			Nob		1	0	yes	0.217	0.099	0	0.38	0.343	0.146	0.12	0.62	1.09	0.51	0.3	2	0.254	0.204	0	0.8
		30			SIC		1	0		0.15	0.12	0	0.47	0.4	0.12	0.08	0.64	1.18	0.55	0.4	1.9				
2	5	50	mand	E	Sur	L	3		osteotomies	0.9	0.5	0.7	1.2	1	0.6	0.7	1.6	4.5	2	3.5	5.4				

Legend: First line of each study represents overall data, if data mentioned for subgroups, they are written below. nArt= number article, nS= number of subjects, nI=number of implants, Templ= surgical template; SLA= stereolithography, L=laboratory, Support: T=tooth involved, E=epoxy, Templ= surgical template, nTempl= number of surgical templates, Pins= fixation pins, Nob=NobelGuide, SIC=SICAT.
Number of study: 1= Dreiseidler et al. 2009, 2= Sarment et al. 2003.

Table 2c. **Descriptive table for *ex vivo* studies.**

										error entry (mm)				error apex (mm)				error angle (°)				error depth (mm)			
nArt	nS	nI	site	support	guid system	Templ	nTempl	Pins	impl guided	mean	SD	min	max	mean	SD	min	max	mean	SD	min	max	mean	SD	min	max
1	17	145	max & mand	M	Nob	SLA	1	3 to 5	yes													0.39	0.59		
	10	78	max							0.83	0.57	0.07	2.78	0.96	0.5	0.12	2.43	2.02	0.66	0.08	5.38				
	7	67	mand							1.05	0.47	0.41	3.13	1.24	0.58	0.13	3.63	2.46	0.67	0.26	7.44				
2	NA	~60	mand	B	Surg	SLA	3	0	no	1.5	0.8			NA				7.9	5						
3	4	12	max & mand	T	Nob	SLA	1	0 or 1	yes	1.1	0.7	0.3	2.3	1.2	0.7	0.3	2.4	1.8	0.8	0.7	4				
4	2	10	max	M	Nob	SLA	1	0	yes	0.8	0.3		1.1	0.9	0.3		1.1	1.8	1						
5	8	51	max & mand	3 screws	Easy	L	1	3	yes	1.1	0.6		2.4	1.2	0.7		3.1	2.8	2.1		9.2				

Legend: First line of each study represents overall data, if data mentioned for subgroups, they are written below. nArt: number of article, nS= number of subjects, nI=number of implants, Guide: SLA= stereolithography, L=laboratory, Support: T=tooth involved, B=bone, Templ= surgical template, nTempl= number of surgical templates, Pins= fixation pins, Guid system= Guiding system; Surg = Surgi-Guide, Nob=NobelGuide, Easy= Easy Taxis Aiming Device.
Number of study: 1=Pettersson et al. 2010b, 2= Ruppin et al. 2008, 3= Van Assche et al. 2007, 4= van Steenberghe et al. 2003, 2005, 5= Widmann et al. 2009.

Study design (*in vitro*, ex vivo, *in vivo*)

The lowest entry deviation reported *in vivo* was 0.01, *in vitro* 0.01 and 0.07 *ex vivo*. The respective maximal value was 6.5, 1.2, 3.1 mm. The lowest apical deviation reported *in vivo* was 0, *in vitro* 0.06 and 0.07 *ex vivo*, whereas the respective maximal value was 6.9, 1.6, 2.78 mm. The lowest angular deviation reported *in vivo* was 0.04°, *in vitro* 0.3° (1 study) and 0.08° *ex vivo*. The respective maximal value was 24.9°, 0.08°, 9.2°.

A forest plot presents the data stratified by study design for all parameters for deviation at entry (Fig. 3), apex (Fig. 4) angulation (Fig. 5) and depth/height (Fig. 6).

Statistically significant difference was found for the entry error (*in vitro* vs *ex vivo*) and apical error (*in vitro* vs *ex vivo*, *in vivo* vs *in vitro*). The number of *in vitro* studies was limited ($n = 2$).

RCTs looking specifically into this parameter (study design), keeping the other parameters identical, are not available.

Support (tooth (T)/mucosa (M/bone (B) supported template)

Statistical analysis found a significant difference for B vs., T ($P < 0.05$) and B vs., M ($P < 0.05$).

Only two studies, both *in vivo*, evaluated the type of support within the same study (Ozan et al. 2007; Ersoy et al. 2008). Ersoy et al. (2008) and co-workers found no significant difference, although Ozan et al. (2007) found a significant difference between T vs., B and T vs., M, with lowest deviation for T supported guides.

Number of templates

A statistical significant difference was found between the use of single/multiple surgical guides for entry, apical and angular deviation.

Two *in vivo* studies used single and multiple guides within the same study (Arisan et al. 2010 and Cassetta et al. 2011a). Both studies used three different supports (T, M and B). The influence of the single/multiple templates is not reported in the first publication for each type of support. Cassetta et al. (2011a) found a statistical significant improvement for bone and mucosa-supported single guides.

So, RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

Use of fixation pins

The mean deviation for all parameters was less when at least one fixation pin was used. A significant difference was not found for any of the parameters.

Table 3a. **Statistical results defined for several subgroups, based on *in vivo* studies**

				entry error					apical error					angular error				
parameter		nStud	nI	mean	SE	95% CI,L	95% CI,U	*P* value	mean	SE	95% CI,L	95% CI,U	*P* value	mean	SE	95% CI,L	95% CI,U	*P* value
support	T	6	340	0.73	0.16	0.42	1.04		0.98	0.20	0.58	1.38		3.08	0.37	2.35	3.82	
	M	7	462	0.97	0.07	0.82	1.11		1.26	0.09	1.09	1.44		3.84	0.34	3.17	4.51	
	B	3	188	1.43	0.14	1.16	1.70		1.73	0.14	1.45	2.01		4.86	0.13	4.6	5.12	
	T vs M							**0.65**					**0.11**					**0.19**
	M vs B							**0.003**					**0.005**					**0.15**
	B vs T							**0.001**					**0.002**					**0.0005**
nTempl	1	8	803	0.89	0.16	0.58	1.19		1.17	0.17	0.83	1.51		3.31	0.34	2.64	3.99	
	>1	4	340	1.41	0.14	1.13	1.69		1.88	0.17	1.54	2.22		5.16	0.42	4.34	5.98	
	1 vs >1							**0.01**					**0.009**					**0.01**
Pins	0	5	619	1.13	0.32	0.50	1.75		1.63	0.37	0.90	2.35		4.47	0.67	3.16	5.77	
	≥1	6	505	1.02	0.11	0.80	1.23		1.29	0.11	1.07	1.52		3.58	0.32	2.95	4.2	
	0 vs ≥1							**0.8**					**0.54**					**0.38**
jaw	max	7	421	0.87	0.14	0.59	1.15		1.18	0.16	0.87	1.48		4.06	0.73	2.63	5.49	
	mand	6	271	0.92	0.17	0.59	1.26		1.17	0.22	0.73	1.61		3.49	0.5	2.52	4.46	
	max vs mand							**0.94**					**0.92**					**0.57**
Templ	SLA	11	1194	1.09	0.10	0.89	1.28		1.43	0.10	1.23	1.63		4.43	0.35	3.75	5.11	
	L	1	132	0.28	0.02	0.24	0.32		0.42	0.03	0.36	0.48		1.94	0.13	1.68	2.2	
	SLA vs L							**0.001**					**0.0002**					0.15
impl guided	yes	6	518	0.87	0.11	0.65	1.09		1.15	0.14	0.87	1.42		3.06	0.27	2.53	3.6	
	no	7	676	1.34	0.06	1.21	1.46		1.69	0.08	1.53	1.85		5.6	0.4	4.82	6.38	
	yes vs no							**0.0002**					**0.0003**					**0.00004**

Legende, nStud= number studies, nI=number of implants, SE= standard error, CI,L= confidence interval lower, CI,U= confidence interval upper valueTempl: SLA= stereolithography, L=laboratory, Support: T=tooth involved, M=mucosa, B=bone, Templ= surgical template, nTempl= number of surgical templates, Pins= fixation pins, Ay-D= Ay-Design, Ayt= Aytasarim, Fac= Facilitate, Sim= Simplant, Surg = SurgiGuide, Safe S= Safe SurgiGuide, Nob=NobelGuide, Sin= SinterStationHiQ.

Table 3b. **Statistical results defined for several subgroups, based on *in vivo*, *in vitro* and *ex vivo* studies**

				entry error					apical error					angular error				
parameter		nStud	nI	mean	SE	95% CI,L	95% CI,U	*P* value	mean	SE	95% CI,L	95% CI,U	*P* value	mean	SE	95% CI,L	95% CI,U	*P* value
support	T	8	406	0.69	0.11	0.47	0.91		0.92	0.14	0.64	1.20		2.68	0.43	1.84	3.52	
	M	9	617	0.94	0.06	0.83	1.05		1.19	0.07	1.06	1.31		3.44	0.33	2.79	4.08	
	B	4	248	1.46	0.09	1.27	1.64		1.73	0.14	1.45	2.01		5.46	0.47	4.53	6.38	
	T vs M							**0.02**					**0.040**					**0.18**
	M vs B							**0.0006**					**0.002**					**0.009**
	B vs T							**0.0001**					**0.001**					**0.0005**
nTempl	1	13	1075	0.86	0.12	0.62	1.10		1.08	0.13	0.82	1.35		2.79	0.29	2.22	3.36	
	>1	6	450	1.33	0.14	1.06	1.60		1.73	0.21	1.31	2.15		5.42	0.39	4.65	6.19	
	1 vs >1							**0.008**					**0.010**					**0.00001**
Pins	0	8	743	1.01	0.21	0.60	1.42		1.32	0.25	0.82	1.81		4.12	0.67	2.8	5.43	
	≥1	8	701	1.01	0.08	0.85	1.18		1.25	0.08	1.09	1.41		3.33	0.33	2.69	3.96	
	0 vs ≥1							**0.77**					**0.89**					**0.45**
jaw	max	9	509	0.86	0.12	0.63	1.09		1.11	0.12	0.89	1.34		3.58	0.67	2.26	4.9	
	mand	9	448	1.00	0.14	0.71	1.28		1.15	0.17	0.82	1.48		3.91	0.45	3.03	4.79	
	max vs mand							**0.49**					**0.88**					**0.65**
Templ	SLA	15	1421	1.08	0.08	0.92	1.24		1.35	0.09	1.18	1.52		4.14	0.34	3.46	4.81	
	L	4	287	0.60	0.12	0.35	0.84		0.72	0.12	0.49	0.96		2.57	0.59	1.41	3.72	
	SLA vs L							**0.0007**					**0.0001**					0.13
impl guided	yes	11	760	0.85	0.12	0.61	1.08		1.05	0.13	0.80	1.30		2.55	0.26	2.04	3.06	
	no	8	736	1.36	0.06	1.24	1.47		1.69	0.08	1.53	1.85		5.86	0.41	5.05	6.68	
	yes vs no							**0.0003**					**0.0001**					**0.00004**

Legende, nStud= number studies, nI=number of implants, SE= standard error, CI,L= confidence interval lower, CI,U= confidence interval upper valueTempl: SLA= stereolithography, L=laboratory, Support: T=tooth involved, M=mucosa, B=bone, Templ= surgical template, nTempl= number of surgical templates, Pins= fixation pins, Ay-D= Ay-Design, Ayt= Aytasarim, Fac= Facilitate, Sim= Simplant, Surg = SurgiGuide, Safe S= Safe SurgiGuide, Nob=NobelGuide, Sin= SinterStationHiQ.

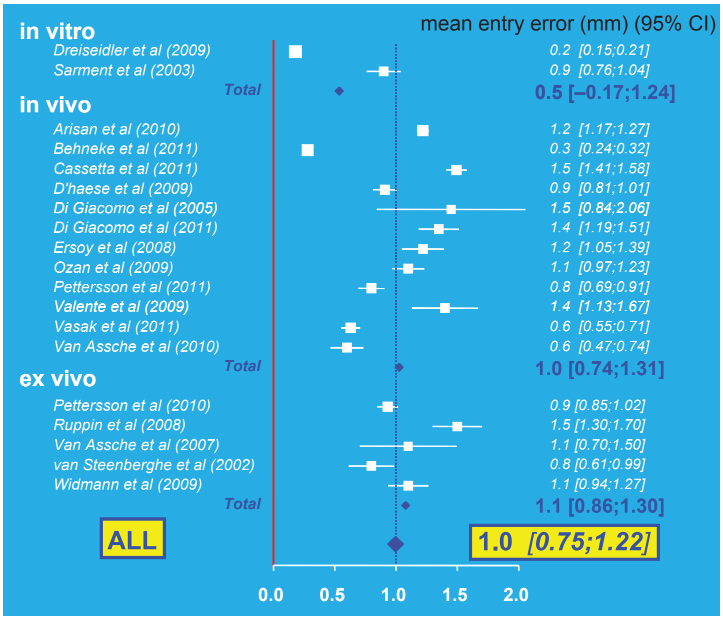

Fig. 3. Mean deviation at entry, stratified by study design

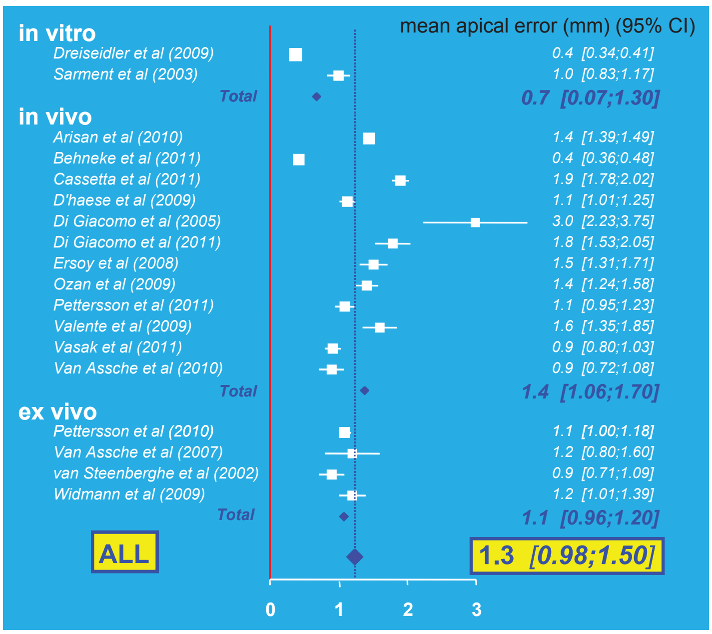

Fig. 4. Mean deviation at apex, stratified by study design

RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

Jaw selection

No significant difference was found between upper and lower jaw for any of the parameters. Fives studies specifically looked into this parameter. Two *in vivo* studies (Ersoy et al. 2008; Arisan et al. 2010) found no statistical significant difference, while one *in vivo* study (Vasak et al. 2011) found lower deviations for mandible. In all three studies different supports were used within the same study. Di Giacomo et al. (2011) reported only on mucosa-supported templates *in vivo* and found a difference for only the angular deviation. Pettersson and co-workers (2010b) reported on mucosa-supported templates *ex vivo* and found a significant difference.

RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

Fabrication of template

Apical and angular deviation were significantly lower for laboratory produced templates. On the other hand, laboratory produced templates were evaluated only in 1 *in vivo* study.

RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

Guiding system

Statistical analysis could detect some statistical significant difference between different guiding systems. Deviation data of most guiding systems are often limited to only one study.

Studies comparing different guiding systems are limited. Arisan et al. (2010) found significantly better results using Safe® and SurgiGuide® compared to Aytasarim® for bone and tooth-supported templates, but this was not concluded for the mucosa-supported templates. Safe SurgiGuide® was significantly better compared to SurgiGuide® (Cassetta et al. 2011a). No difference was found between SICAT® and NobelGuide® (Dreiseidler et al. 2009).

RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

Guided implant placement

The mean deviation at the entry point *in vivo* was 0.87 mm (SE 0.11, max 3) when the implant placement was guided, vs., 1.34 (SE 0.06, max 6.5) when unguided. The mean respective deviation at the apex of the implants was 1.15 (SE 0.12, max 4.2), vs., 1.69 mm (SE 0.08, max 6.9). The mean deviation in angulation was 3.06 ° (SE 0.27, max 15.25), 5.6 (SE 0.4, max 24.9) respectively.

Deviation parameters (entry, apical and angle) were significantly lower for implants, which were guided during the insertion.

Three studies placed implants, both guided and not guided within the same study, but other parameters (e.g. support, guiding system) were not the same in both groups (Arisan et al. 2010; Behneke et al. 2011; Cassetta et al. 2011a), which makes comparison impossible.

RCTs looking specifically into this parameter, keeping the other parameters identical, are not available.

When the statistical analysis, looking for the influence of different parameters, was repeated including *in vitro* and *ex vivo* studies, the significance (*P*-values) did not change, except for support (Table 3b).

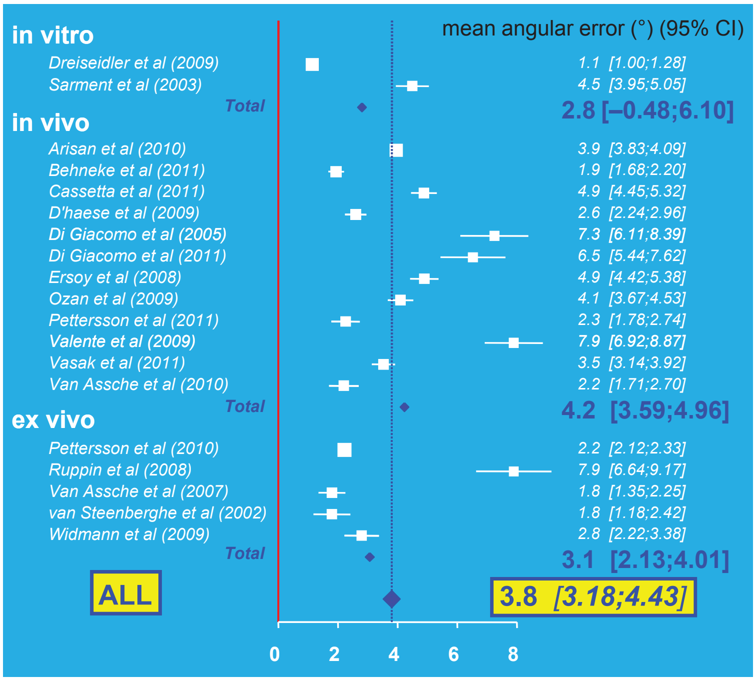

Fig. 5. Mean angular deviation, stratified by study design

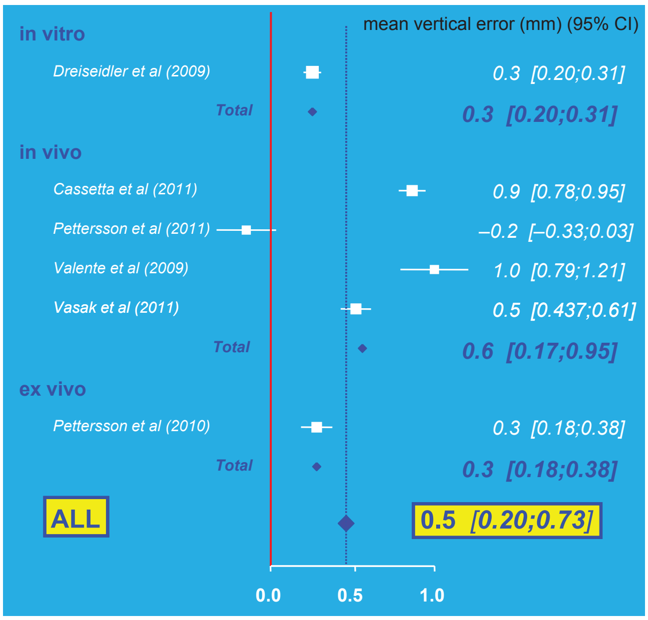

Fig. 6. Mean angular deviation, stratified by study design

Discussion

This review systematically assessed the literature regarding the accuracy of computer-guided implant placement. Deviations of 10 different static image guided systems have been reported. In general the angular deviation of all systems was 3.81° with a maximum of 24.9°. One might consider these deviations as very large, but an *in vivo* RCT with comparison between computer-guided and brain-guided surgery (with or without any type of surgical template) is not available. Two small vitro studies (Sarment et al. 2003; Nickenig et al. 2010) compared deviations for brain guided with deviations for computer-guided surgery. A significant improvement was observed in favour of guided surgery for all deviations. When for example the angular deviations were compared they were 4.5° for guided and 8.0° (Sarment et al. 2003), 4.2° and 10.4° respectively (Nickenig et al. 2010).

RCTs looking into the importance of one specific factor are lacking. Therefore, all analyses on the impact of specific factors (*in vitro* vs. *ex vivo* vs. *in vitro*; teeth vs. mucosa vs. bone supported; single vs. multiple templates, type of guidance, guided vs. non-guided implant placement, etc.) had to be performed indirectly without taking interactions between these factors into consideration. The conclusions therefore have to be considered with caution. There is also clear inconsistency in the reported observations. For example, when comparing the data of the maxilla with the mandible. Some publications reported no differences (Ersoy et al. 2008; Arisan et al. 2010), although Pettersson and co-workers (2010a) and Vasak et al. (2011) observed significant difference between both jaws (in favour of the mandible). Di Giacomo et al. (2011) observed significant higher deviations in the maxilla.

Computer-guided implant placement has often been recommended for flapless procedures and for implant placements in situations with a limited amount of bone, or in the proximity to critical anatomical structures. Therefore, it is of utmost importance to know the maximal possible deviation of the system used in clinical practice. As such, one could have an idea of the minimal jaw bone width needed before blind surgery can be performed. No article reported on the width of the crest. Arisan et al. (2010) was the only study where the bone width was mentioned as inclusion criteria (≥ 4.5 mm) for flapless mucosa-supported templates. In other publications "sufficient bone width" was mentioned without exact width measurement. Other bone characteristics can also have a significant impact. For example, in a very narrow ridge, where due to the cortex the drill can deviate (way of least resistance) due its tolerance within the guiding device, deviations might be higher compared to a wide ridge flat crest. Also, the height of the remaining crest in a full edentulous patient might be important. This height gives stability to a surgical template. In an extreme resorbed jaw, the deviations might be increased, compared to the deviations in a jaw with almost no resorption. These parameters have never been reported.

The tolerance of the drills within the drill guide and/or sleeve, as reported in two *in vitro* studies (Van Assche and Quiryna 2010; Koop et al. 2012) underline the importance of the position of the drill within the guide. The latter may explain a deviation of the implants to the right for right-handed surgeons or to mesial (especially for the more distal implants). Data on this are limited, and only reported in a study by Di Giacomo et al. (2011) who found a significant lower angular deviation for anterior implants, and a study by Vasak et al. (2011) who found significant lower deviations for anterior implants compared to posterior ones. D'haese et al. (2009) could not (slight tendency) find a difference. The angular deviation might be the most honest parameter to report a deviation, because this is not influenced by the length of an implant. It has been shown that the longer the implant, the higher the horizontal deviation (Van Assche et al. 2010; Koop et al. 2012).

As mentioned before, the total deviation is the cumulative result of deviations that can occur at each step (Widmann and Bale 2006). Several studies reported the deviation of an individual step. The deviation due to inaccuracy of template fabricated by stereolithography is less than 0.25 mm (Schneider et al. 2002). The maximal deviation of the drill with the surgical guides can reach a maximum horizontal deviation of 1.3 mm at the implant shoulder and 2.7 mm at the apex for a 13 mm implant. A maximum deviation in angulation of 5.5° is tolerated (Van Assche et al. 2010). The latter is specific for each guiding system, whether there is a two leeway or not. A movement of the patient during scanning can result in incorrect planning, or perception of incorrect bone volume. Also the positioning of the template and it's stabilization is very important.

One publication (D'haese et al. 2009) evaluated the deviation within the same patient for all implants (inter-implant deviation), to see whether the deviation is related to malpositioning of the whole template, or to individual deviation of each implant. They observed that the mean deviation (e.g. apical deviation= 1.3 mm) was substantially different from the inter-implant distance deviation (e.g. respective apical deviation 1.3 vs., 0.33 mm). Since only production errors and errors during the surgical procedure contribute to the inter-implant deviations, these results indicate that the total accuracy of full mucosa supported templates is mainly determined by the positioning error of the template. Future studies should look into both aspects.

But there are of course other explanations. Horwitz et al. (2009) observed that attrition of sleeves and drills, after longer use, as contributing factors. Even the mucosal thickness (depending on the biotype or related to smoking), can influence the accuracy of mucosa supported templates (D'haese and De Bruyn 2011; Vasak et al. 2011). The mean deviation at entry for example was 1.04 mm in thick vs., 0.08 mm in thin mucosa (D'haese and De Bruyn 2011).

In the present review, the overall mean error at entry point was 0.99 mm. The importance of this value becomes more understandable when compared to the accuracy of mental navigation (with or without a surgical template). So far this aspect has not been examined via a RCT, and therefore we have to rely on *in vitro* observations. Two preclinical studies on acrylic models compared the accuracy of a static guided implant placement with non-guided implantation (Sarment et al. 2003; Nickenig et al. 2010). Both *in vitro* studies found significant better results for guided implants placement. Unfortunately, one can only speculate on what the accuracy would be for mental navigation.

All studies included in this review used a second CBCT, but one should realize that "model matching" can be a good alternative (without extra radiation to the patient). The latter is well illustrated by Komiyama et al. (2011) who compared the accuracy analysed via CBCT (Pettersson et al. 2010a) with an accuracy evaluation by comparing matching pre- and postoperative models of the patient jaw (Komiyama et al. 2011). The respective mean deviations were quite similar (for model matching at entry 0.5 mm (range 0.1–1.2) and at apex 0.5 mm (range 0.1–1.3 mm); for CT-matching 0.8 mm (range 0.1–2.7 mm) and 1.1 mm (0.2–3.6 mm) for CT-matching.

Tahmasseb et al. (2011) described the use of computer-aided three-dimensional planning protocol in combination with previously placed reference elements. The mean misfit for all implants in the x-, y- a and z-axes was 26.6, 24.8 and 10.4 μm respectively. This means that the use of fiducial markers, consisting of mini-implants, might improve the implant positioning after placement by guided surgery.

The literature is not consistent on whether a learning curve is important, one study found an effect of learning curve (Vasak et al. 2011), while two other studies did not (Valente et al. 2009; Cassetta et al. 2011a). Also, information on complications/adverse events is very scarce; most frequently reported ones are metal tube detachment and fracture of the template (D'haese et al. 2009; Arisan et al. 2010; Di Giacomo et al. 2011).

A comparison between the static computer-assisted implant systems included in this review (Ay-Design®, Aytasarim®, Easy-Taxis®, SinterStationHiQ®, SurgiGuide®, Safe SurgiGuide®, SICAT®, Med3D®, NobelGuide®, Facilitate®) is simply impossible because of the tremendous heterogeneity in study designs (human vs model vs cadaver, drill holes vs implant positions, different matching procedures) and the low number of cases. The statistical analysis, however, detected one important variable, namely improved outcome with guidance of implant during insertion. The latter was detected by Ozan et al. (2007) who used two types of surgical guides (with or without guidance of the implant and drill stop) and who observed that full guidance significantly improved the outcome. Each guiding system has its advantages and tolerance, therefore more randomized studies are needed, using the same study design including a large patient population, allowing the calculation of deviations for equivalent subgroups (same surgeon, same guiding device, same scanning, matching procedure).

If computer-assisted implant placement would be accurate and reproducible, this might improve oral rehabilitations, anatomical injuries can be avoided, and immediate prosthetic rehabilitation will be possible. Even then the advantages have to be balanced towards the costs, preparations, total time and limitations (mouth opening, posterior sites). Especially in mucosa-supported guides, with flapless preparation and implant placement, all steps are to be performed in a very precise manner. De Almeida et al. (2010) concluded that in extreme resorption, a flap approach can be more precise.

Conclusion

Today, different computer-assisted implant placement procedures are available. They differ in software, template manufacturing, guiding device, stabilization and fixation. There are no *in vivo* RCTs in the dental literature that report the accuracy of computer-guided implant placement compared to a "brain guided approach". Irrespective of the study design the mean deviation of implants inserted using guided surgery techniques was: 1.09mm at entry, a mean deviation of 1.28 mm at the apex and 3.9° in angulation. However, there was significant variation in the results. Factors reported influencing the accuracy of the computer-guided approach in a negative way are bone-supported guides, the use of multiple templates and the lack of guide fixation. The various studies addressing computer-guided implant placement looked at many different variables making inter study comparison difficult if not impossible.

In the literature, there is little information on vertical deviation when using computer-guided implant systems. Little is reported on the required bone volume and its effect on precision when using guided implant surgery techniques.

The present systematic review highlighted on factors with a significant impact on the final accuracy: the guidance of the implant during insertion seems to be crucial. The review also illustrates that one has to accept a certain inaccuracy of 2 mm, which seems big at first view, but is clearly lesser than that for non-guided surgery. A reduction of the accuracy below 0.5 mm seems extremely difficult. To find the best guiding system/most important parameters for optimal accuracy, more RCTs are necessary.

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