David Schneider
Pascal Marquardt
Marcel Zwahlen
Ronald E. Jung

A systematic review on the accuracy and the clinical outcome of computer-guided template-based implant dentistry

Authors' affiliations:
David Schneider, Ronald E. Jung, Department of Fixed and Removable Prosthodontics and Dental Material Science, Dental School, University of Zurich, Zurich, Switzerland
Pascal Marquardt, Private Practice, Cologne, Germany
Marcel Zwahlen, Institute of Social and Preventive Medicine, University of Berne, Finkenhubelweg 11, Berne, Switzerland

Correspondence to:
Dr med., med. dent. *David Schneider*
Department of Fixed and Removable Prosthodontics and Dental Material Science
Dental School
University of Zurich
Plattenstrasse 11,
8032 Zurich
Switzerland
Tel.: +41 44 634 32 51
Fax: +41 44 634 43 05
e-mail: david.schneider@zzmk.uzh.ch

Conflicts of interest:
The authors declare no conflicts of interest.

Date:
Accepted 20 May 2009

To cite this article:
Schneider D, Marquardt P, Zwahlen M, Jung RE. A systematic review on the accuracy and the clinical outcome of computer-guided template-based implant dentistry.
Clin. Oral Impl. Res. **20** (Suppl. 4), 2009; 73–86.
doi: 10.1111/j.1600-0501.2009.01788.x

Key words: computer-guided implant dentistry, dental implants, image-guided surgery

Abstract
Introduction: The aim of this systematic review was to analyze the dental literature regarding accuracy and clinical application in computer-guided template-based implant dentistry.
Materials and methods: An electronic literature search complemented by manual searching was performed to gather data on accuracy and surgical, biological and prosthetic complications in connection with computer-guided implant treatment. For the assessment of accuracy meta-regression analysis was performed. Complication rates are descriptively summarized.
Results: From 3120 titles after the literature search, eight articles met the inclusion criteria regarding accuracy and 10 regarding the clinical performance. Meta-regression analysis revealed a mean deviation at the entry point of 1.07 mm (95% CI: 0.76–1.22 mm) and at the apex of 1.63 mm (95% CI: 1.26–2 mm). No significant differences between the studies were found regarding method of template production or template support and stabilization. Early surgical complications occurred in 9.1%, early prosthetic complications in 18.8% and late prosthetic complications in 12% of the cases. Implant survival rates of 91–100% after an observation time of 12–60 months are reported in six clinical studies with 537 implants mainly restored immediately after flapless implantation procedures.
Conclusion: Computer-guided template-based implant placement showed high implant survival rates ranging from 91% to 100%. However, a considerable number of technique-related perioperative complications were observed. Preclinical and clinical studies indicated a reasonable mean accuracy with relatively high maximum deviations. Future research should be directed to increase the number of clinical studies with longer observation periods and to improve the systems in terms of perioperative handling, accuracy and prosthetic complications.

Prosthetic rehabilitation with implant-supported prostheses is considered to be a routine procedure with high success rates (Hammerle et al. 2002; Pjetursson et al. 2007; Jung et al. 2008). Before implant placement the preoperative diagnostics usually include an analysis of conventional two-dimensional radiographs regarding the availability of bone and identification of relevant anatomic structures. Radiographic templates representing the prosthetic set-up are often applied in terms of planning the optimal implant position on radiographs. The same templates can be used as a prosthetic reference during implant surgery. However, with this kind of pre-operative planning the third dimension of the patient's anatomy is missing. Although in medicine, computer tomography has been providing three-dimensional anatomic information for more than three decades, its application in dentistry was restricted to selected cases. With increasing availability, reduced radiation and lower costs of three-dimensional imaging because of cone beam computer tomography, preoperative three-dimensional implant planning is becoming more popular in dentistry and cranio-maxillo-facial surgery (Schulze et al. 2004; Guerrero et al. 2006). Software allowing virtual implant placement using the acquired digital data from the computed tomography (CT) scan has been developed by several manufacturers. To transfer the preoperatively planned implant position into the patient's mouth surgical templates, based on the preoperative set-up and virtual implant planning, are either fabricated manually in a dental laboratory or stereolithographically by computer-aided design (CAD)-computer-aided manufacturing (CAM) technology. Other systems use intra-operative optical tracking of the hand-piece position with cameras and guide the surgeon 'real-time' providing visual feedback on a screen. The latter are called 'navigation' or 'dynamic' systems while the systems using drill-guides are referred to as 'template-based' or 'static' (Jung et al. in press).

The assumed benefit of the computer-assisted implant planning and subsequent template-guided implant placement is a thorough preoperative diagnostic and a more predictable implantation procedure with respect to anatomical structures and prosthetic aspects. Bone augmentation procedures can eventually be avoided in some patients by an optimal utilization of present bone. In selected cases even flapless procedures can be considered. Adequate precision of implant placement provided, prefabrication of prosthetic reconstructions and immediate loading may be possible (van Steenberghe et al. 2005; Sanna et al. 2007; Komiyama et al. 2008).

Although computer-guided implant dentistry is an upcoming technology with the potential for more predictive and less invasive implant placement, its performance has to be critically evaluated, because it is already in clinical practice.

The aim of this systematic review was to analyze the dental literature regarding accuracy and clinical application in computer-guided template-based implant dentistry.

Materials and methods

Search strategy

According to a previous systematic review (Jung et al. in press) an online search of the PubMed electronic library was performed using the following terms: (1) 'dental AND implant* AND compute*' (2) 'dental AND implant* AND guid*' (3) 'dental AND implant* AND navigat*'.

The initial search included studies from 1966 up to December 2007 (Jung et al. in press) and was complemented by a second search limited to dental journals in English language published from January 2008 to February 2009. In addition, a manual search of topic-related dental journals and the reference list of all selected full-text articles was conducted. Two reviewers performed the literature search independently (Fig. 1).

Inclusion and exclusion criteria

For the first outcome variable, the *accuracy* of computer-guided template-based implant dentistry, *in vitro*, cadaver, animal and clinical studies were included. No restrictions were made regarding the study design or follow-up period. Only studies providing exact information about the amount and direction of implant or bore-hole deviations were included.

For studies on *clinical performance* no restrictions were made regarding the study design but only studies with a minimum of five patients were included. Furthermore, for the evaluation of late implant and prosthetic complications a minimum follow-up period of 12 months was defined.

Only studies performed with 'static' surgical template-based computer-guided implant systems were included in the present systematic review. Studies using 'dynamic'

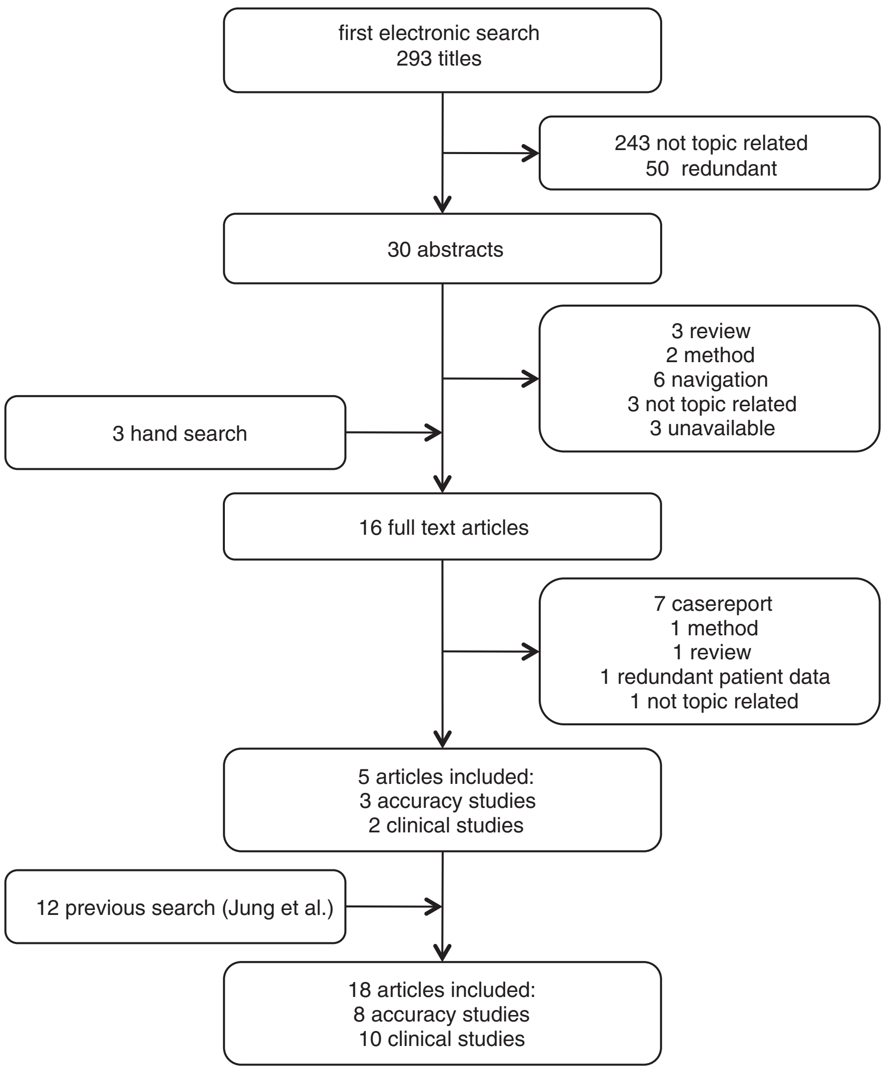

Fig. 1. Literature search and article selection.

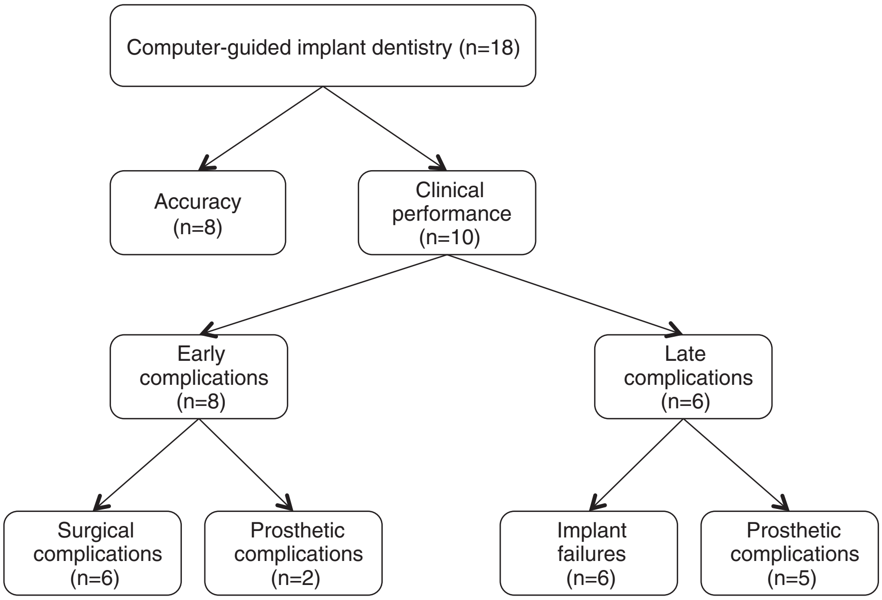

Fig. 2. Distribution of studies according to outcome measures.

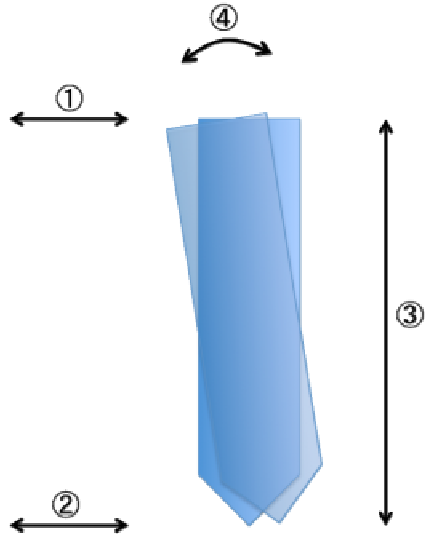

Fig. 3. Direction of deviations in the variable 'accuracy'. (1) Deviation at entry point, (2) deviation at apex, (3) deviation in height and (4) angular deviation.

navigation systems were excluded as well as studies with zygoma implants, pterygoid implants or mini-implants for orthodontic purposes or epitheses. Neither reviews nor case reports with less than five patients or method descriptions were included. Publications were also excluded if the study exclusively reported on the radiographic planning.

Outcome variables

The following two outcome variables were defined (Fig. 2): accuracy and clinical performance. For *accuracy*, the following four parameters were evaluated (Fig. 3): (1) Deviation at entry point, (2) deviation at apex, (3) deviation in height and (4) deviation of the axis.

For the *clinical performance*, several outcome parameters were determined (1) Early (set at 2 weeks postoperatively) surgical complications or unexpected events, (2) early prosthetic complications, (3) late (set at 12 months or more) implant failures and (4) late prosthetic complications.

Data extraction

Two reviewers extracted the data independently using data extraction tables. Any disagreements were resolved by discussion aiming for consensus.

Statistical analysis

The data were analyzed according to the methods used in a previous systematic review (Jung et al. in press). In brief, inverse variance weighted random effects meta-analysis was performed and meta-regression was used for the comparison of mean accuracy between different groups. To obtain the variance, the standard error (SE) was derived from the observed standard deviation (SD) of the accuracy values using the formula: $SE = SD/n$, where n is the number of observations in the study. Heterogeneity between studies was assessed with the I2 statistic as a measure of the proportion of total variation in estimates that is due to heterogeneity (Higgins & Thompson 2002). Results of clinical performance are descriptively summarized. Summary estimates and 95% confidence intervals (95% CI) and P-values from meta-regression for assessing differences in outcomes between groups of studies are reported. The level of significance was set at $P<0.05$. All analyses were done using Stata (StataCorp, College Station, TX, USA) version 10.

Results

In addition to the systematic search performed from 1966 up to December 2007 (Jung et al. in press) (2827 titles) 293 titles from January 2008 to February 2009 were acquired from the electronic search. The screening and evaluation of these titles led to a reduction to 30 titles. After abstract review, 13 remained and proceeded to full text analysis. Finally three accuracy and two clinical studies were additionally included for this review (Figs 1 and 2, Table 7).

After merging with the already acquired articles from 1966 to December 2007 (Jung et al. in press) a total of eight articles reporting on accuracy and 10 clinical studies on computer-guided template-based implant insertion were available for this systematic review (Fig. 1).

Accuracy studies

In eight articles, published from 2002 to 2009, information on deviation according to the inclusion criteria was found (Table 1).

One study was performed on model (50 implantation sites) (Sarment et al. 2003), four on cadavers (116 implantation sites) and three in humans (155 implant sites). A total of 321 sites were analyzed, 50 of which were boreholes and 271 implants. four different systems were used (SimPlant/Surgiguide, NobelGuide, Stent CAD and Med3D). One study (48 sites) used laboratory-fabricated surgical guides based on the computer-assisted implant planning (Kalt & Gehrke 2008) all others (275 sites) stereolithographically fabricated guides (rapid prototyping).

CT scans were used in all studies for the evaluation of the deviations.

Table 1. Accuracy studies

No.	Author (year)	System	Template production	Study design	Positioning method	Template support	Number of sites	Error entry mean (mm)	Error entry SD (mm)	Error entry max (mm)	Error apex mean (mm)	Error apex SD (mm)	Error apex max (mm)	Error angle mean (°)	Error angle SD (°)	Error angle max (°)	Error height mean (mm)	Error height SD (mm)	Error height max (mm)
1	Di Giacomo et al. (2005)	SimPlant	Rapid prototyping	Human	Implant	Bone and/or teeth	21	1.45	1.42	4.5	2.99	1.77	7.1	7.25	2.67	12.2	–	–	–
2	Sarment et al. (2003)	SimPlant	Rapid prototyping	Model	Bore	Model	50	0.9	0.5	1.2	1	0.6	1.6	4.5	2	5.4	–	–	–
3	Vrielinck et al. (2003)	SurgiGuide, Materialise	Rapid prototyping	Human	Implant	Bone/pins	24	1.51	–	4.7	3.07	–	6.4	10.46	–	21	–	–	–
4	Van Assche et al. (2007)	Nobel	Rapid prototyping	Cadaver	Implant	Teeth or mucosa and/or pins	12	1.1	0.7	2.3	1.2	0.7	2.4	1.8	0.8	4	–	–	–
5	van Steenberghe et al. (2002)	Nobel	Rapid prototyping	Cadaver	Implant	Bone/pins	16	0.8	0.3	–	0.9	0.3	–	1.8	1	–	–	–	1.1
6	Ozan et al. (2009)	Stent CAD	Rapid prototyping	Human	Implant	Bone	50	1.28	0.9	2.9	1.57	0.9	3.6	4.63	2.6	9.9	–	–	–
				Human	Implant	Teeth	30	0.87	0.4	1.8	0.95	0.6	2.2	2.91	1.3	5.6	–	–	–
				Human	Implant	Mucosa	30	1.06	0.6	2.6	1.6	1	4.1	4.51	2.1	9	–	–	–
7	Kalt & Gehrke (2008)	med3D	Dental laboratory	Cadaver	Implant	Implant	48	0.83	0.49	1.69	2.17	1.02	3.79	8.44	3.98	15.98	0.28	0.51	1.94
8	Ruppin et al. (2008)	SimPlant	Rapid prototyping	Cadaver	Implant	Bone	40	1.5	0.8	3.5	–	–	–	7.9	5	18.5	0.6	0.4	1.4

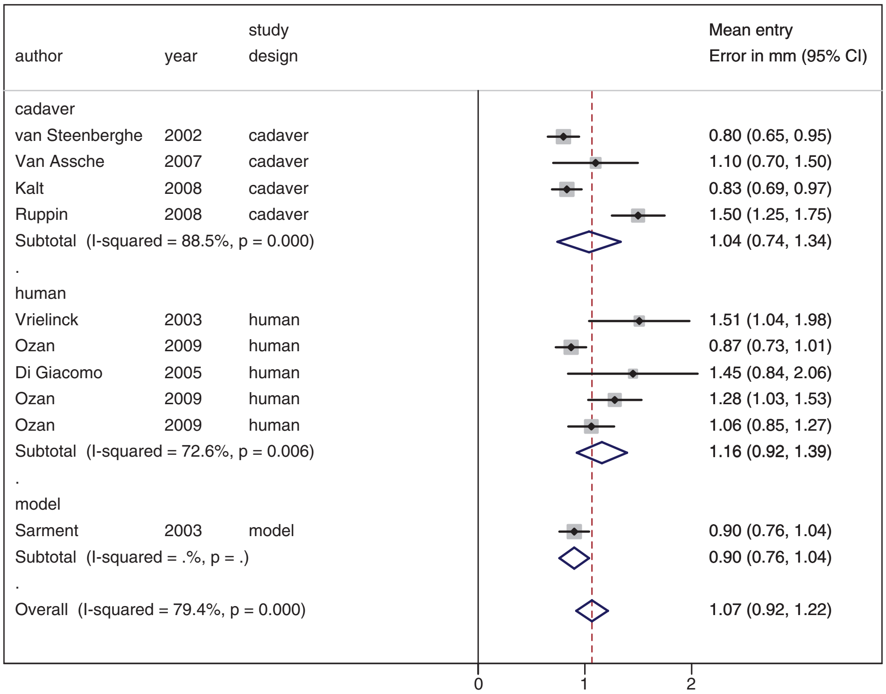

Fig. 4. Deviation at entry point, stratified by study design (human, cadaver or *in vitro* study).

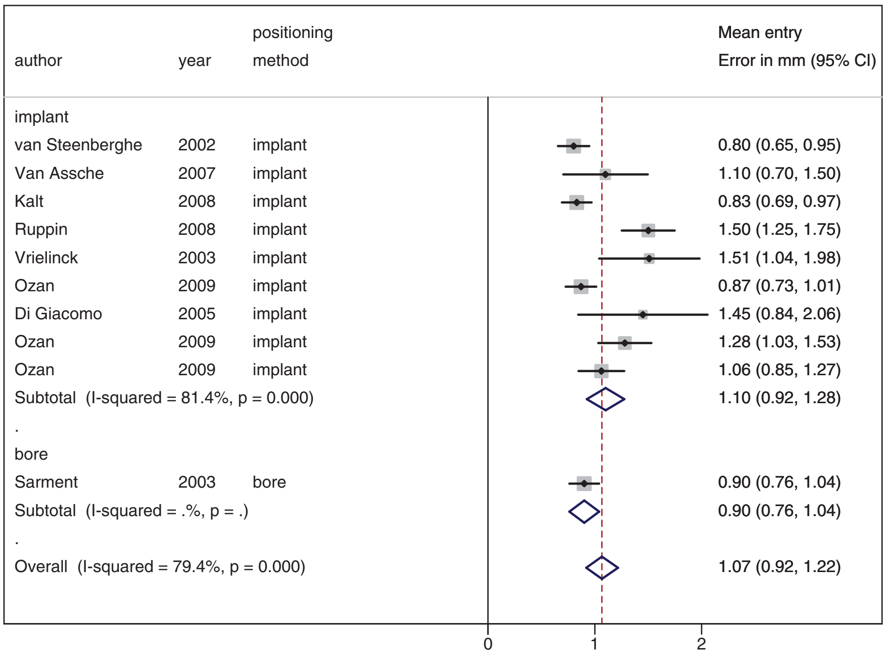

Fig. 5. Deviation at entry point, stratified by positioning method (implants or bore holes).

Error at entry point and apex

The over all mean error at the entry point (eight studies, 321 sites) was 1.07 mm (95% CI: 0.76–1.22 mm) and at the apex (seven studies, 281 sites) 1.63 mm (95% CI: 1.26–2 mm).

At the entry point the mean deviation was similar in studies performed in humans (three studies, 155 sites) (1.16 mm, 95% CI: 0.92–1.39 mm), cadavers (four studies, 116 sites) (1.04 mm, 95% CI: 0.74–1.34 mm) and models (one study, 50 sites) (0.90 mm, 95% CI: 0.76–1.04 mm) (Fig. 4). At the apex the mean deviation was 1.96 mm (95% CI: 1.33–2.58 mm) in studies performed in humans (three studies, 155 sites), 1.42 mm (95% CI: 0.59–2.25 mm) in cadavers (three studies, 76 sites) and 1 mm (95% CI: 0.83–1.17 mm) in models (one study, 50 sites) (Fig. 8).

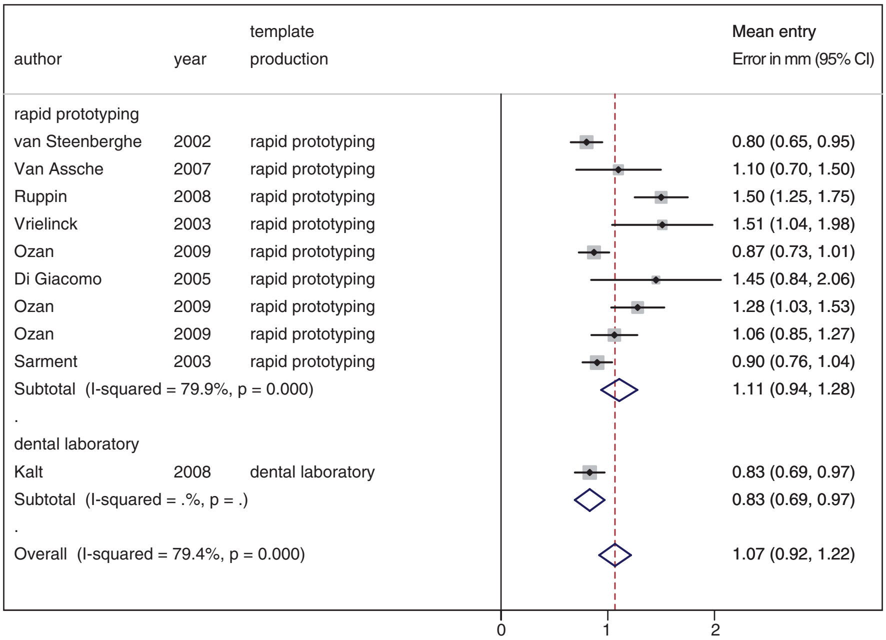

Fig. 6. Deviation at entry point, stratified by template production (rapid prototyping or dental laboratory).

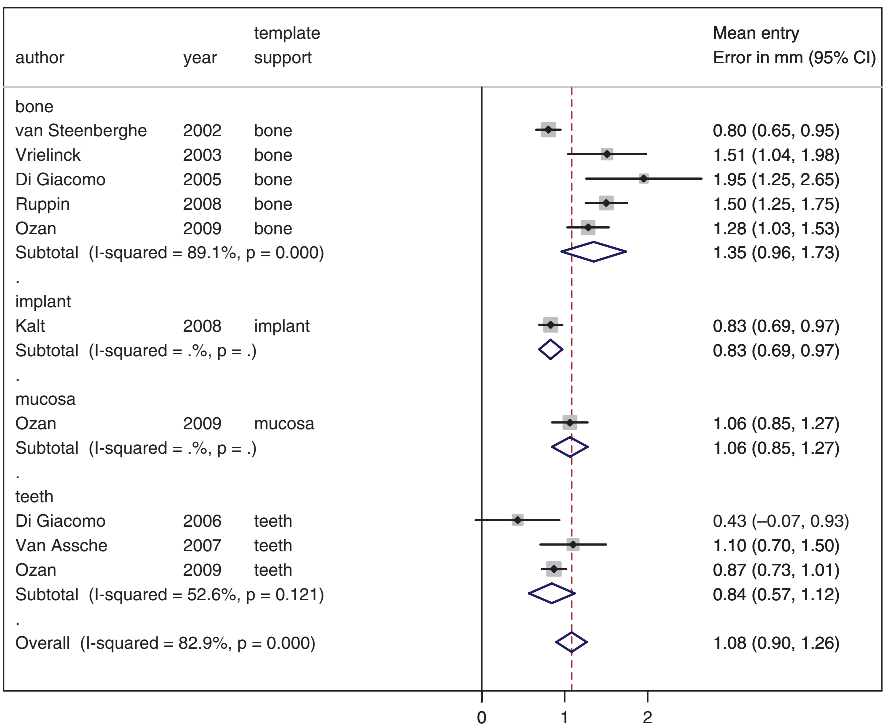

Fig. 7. Deviation at entry point, stratified by template support (bone, implant, mucosa or teeth).

Some studies analyzed the position of the implants, while others referred to drill-holes only. In studies, in which the position of implants has been evaluated (seven studies, 271 sites), the mean error was 1.10 mm (95% CI: 0.92–1.28 mm) at the entry point and 1.73 mm (95% CI: 1.29–2.18 mm) at the apex. In one study (Sarment et al. 2003), where the position of 50 drill-holes was assessed the mean error was 0.9 mm (95% CI: 0.76–1.04 mm) at the entry point and 1 (95% CI: 0.83–1.17 mm) at the apex (Figs 5 and 9).

In a model study with a laboratory-fabricated guide (48 sites) (Kalt & Gehrke 2008) the mean error at the entry point was 0.83 mm (95% CI: 0.69–0.97) and 2.17 mm (95% CI: 1.88–2.46 mm) at the apex. Studies with guides from rapid prototyping (seven studies, 273 sites) showed a mean error at the entry point of 1.11 mm (95% CI: 0.94–1.28 mm) and 1.53 mm (95% CI: 1.19–1.87 mm) at the apex (Figs 6 and 10).

Surgical templates supported by teeth (three studies, 46 sites), bone (five studies, 144 sites) or implants (one study, 48 implants) (Kalt & Gehrke 2008) did not show a significantly different accuracy, neither at the entry point nor at the apex compared with mucosa-supported templates (one study, 30 sites) (Ozan et al. 2009) (Figs 7 and 11). The mean error at the entry was 1.35 mm (95% CI: 0.96–1.73 mm) with bone-supported, 0.84 mm (95% CI: 0.57–1.12 mm) with teeth-supported, 0.83 mm (95% CI: 0.69–0.97 mm) with implant-supported and 1.06 mm (95% CI: 0.85–1.27 mm) with mucosa-supported templates and at the apex 2.06 mm (95% CI: 1.24–2.87 mm), 1.71 mm (95% CI: 0.79–1.61 mm), 2.17 mm (95% CI: 1.88–2.46 mm) and 1.60 mm (95% CI: 1.24–1.96 mm), respectively.

No statistically significant differences were found regarding horizontal deviation at the entry point and the apex in terms of the study design (human, cadaver or *in vitro*), the method of positioning (implants or bore holes), the method of template production (rapid prototyping or dental laboratory) or the template support (bone, teeth, implants or mucosa).

Error in height

The mean error in height was reported in two studies (88 sites), both performed with implants on cadavers. The mean error in height for the two studies was 0.43 mm (95% CI: 0.12–0.74 mm). In the study using laboratory-fabricated guides (48 sites) (Kalt & Gehrke 2008) the mean error in height was 0.28 mm (95% CI: 0.14–0.42 mm) and in the study with guides made by rapid prototyping (40 sites) 0.60 mm (95% CI: 0.48–0.72 mm) (Ruppin et al. 2008).

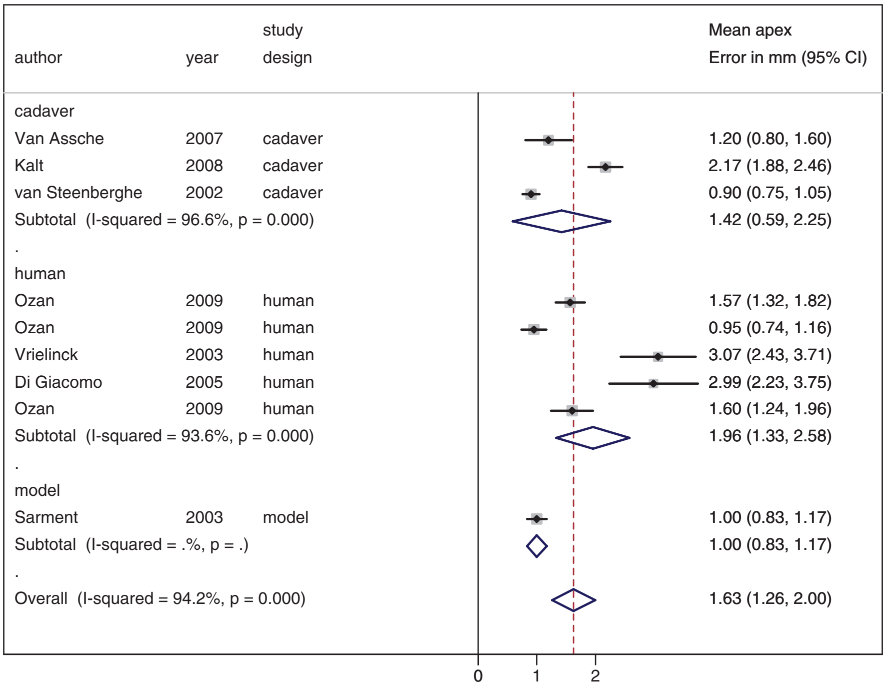

Fig. 8. Deviation at apex, stratified by study design (human, cadaver or *in vitro* study).

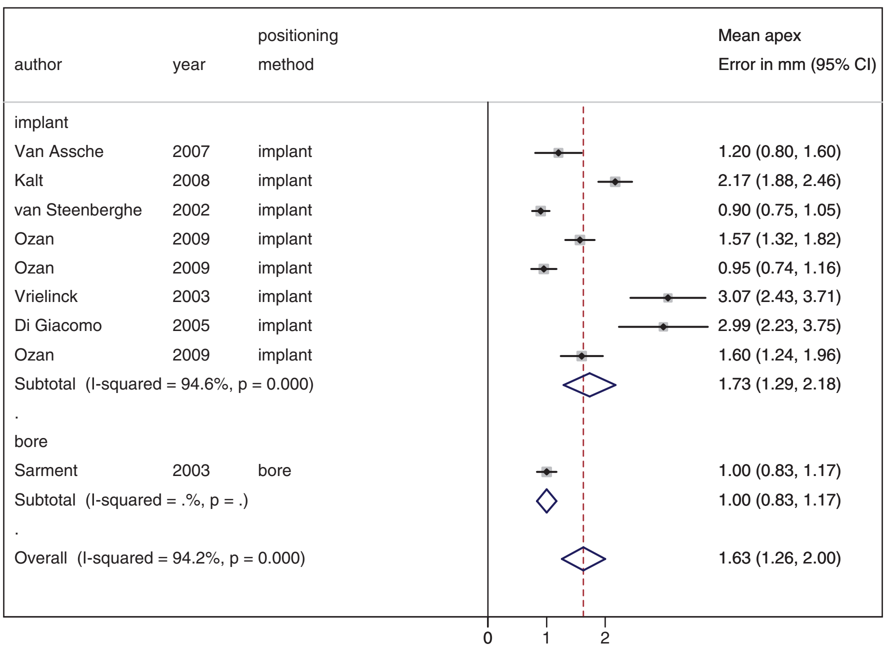

Fig. 9. Deviation at entry point, stratified by positioning method (implants or bore holes).

Error in angulation

Information about the deviation in angulations was found in eight studies (321 sites). The overall mean error in angulation was 5.26° (95% CI: 3.94–6.58°). In three clinical studies (155 sites) the mean error in angulation was 5.73° (95% CI: 3.96–7.49°), in four cadaver studies (116 sites) 4.9° (95% CI: 2.24–7.55°) and in one study on models (50 sites) (Sarment et al. 2003) 4.5° (95% CI: 3.95–5.05°)(Fig. 12). In one study with 50 boreholes (Sarment et al. 2003) the mean error was 4.5° (95% CI: 3.95–5.05°), in seven studies with implants (271 sites) 5.37° (95% CI: 3.87–6.86°) (Fig. 13). Laboratory-fabricated guides (one study, 48 sites) showed a mean error of 8.44° (95% CI: 7.31–9.57°), stereolithographically fabricated guides (seven studies, 753 sites) 4.87° (95% CI: 3.62–6.12°) (Fig. 14).

For teeth-supported guides (three studies, 46 sites) the mean deviation was 2.82° (95% CI: 1.57–4.07°), for bone-supported guides (five studies, 144 sites) 6.39° (95% CI: 3.61–9.17°), for implant-supported guides (one study, 48 sites) 8.44° (95% CI: 7.31–9.57°) and for mucosa-supported guides (one study, 30 sites) 4.51° (95% CI: 3.76–5.26°) (Fig. 15).

The differences between the groups regarding study design, method of positioning, method of template production and template support did not reach statistic significance.

Clinical studies

Ten prospective clinical studies (case series or cohort studies) published from 2003 to 2009 fulfilled the inclusion criteria regarding the clinical outcome. In these publications a total number of 468 patients were treated with 1793 implants placed with computer-guided implant surgery using surgical templates.

The mean patient age was 55.3 years and ranged from 18 to 90 years. The follow-up period ranged from 0 to 60 months. Nine studies reported on the treatment of completely edentulous cases, five studies of partially edentulous cases. In six out of 10 studies flapless implantation procedures were performed, in four studies in combination with an immediate restoration.

Six different systems for computer-guided implant surgery were used (CADImplant, Praxim; NobelGuide, Nobel Biocare; Med3D, Med3D GmbH; coDiagnostiX, IVS-Solutions; SimPlant, Materialise; Stent CAD, Media Lab). In seven out of 10 studies stereolithographically produced surgical templates (rapid prototyping) including 163 patients and 863 implants were used. In four studies laboratory-fabricated surgical guides for implant placement based on the computer-assisted implant planning were applied in 295 patients with 930 implants. In one study both template fabrication methods were used (Mischkowski et al. 2006). In one study with 10 patients the number of implants was not reported (Fortin et al. 2004).

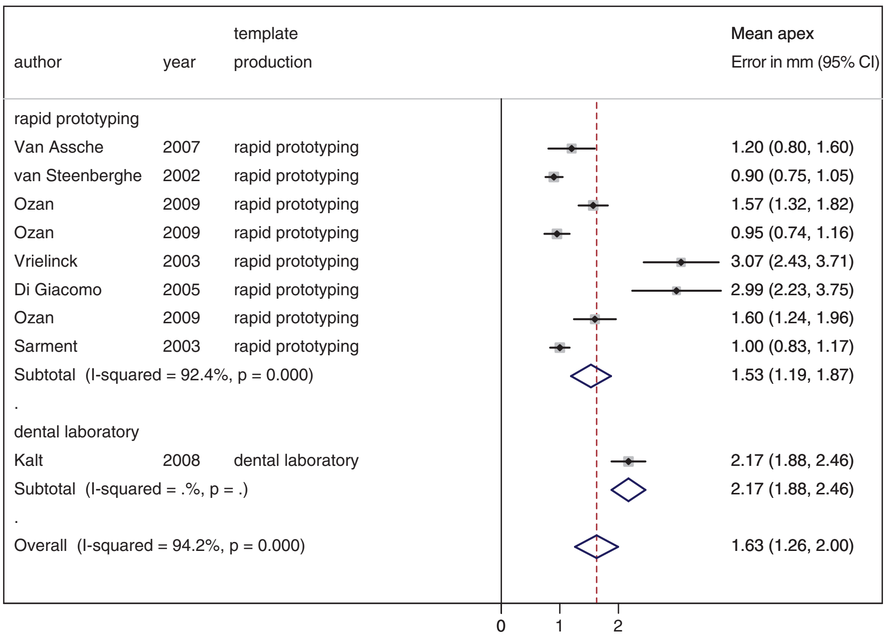

Fig. 10. Deviation at apex, stratified by template production (rapid prototyping or dental laboratory).

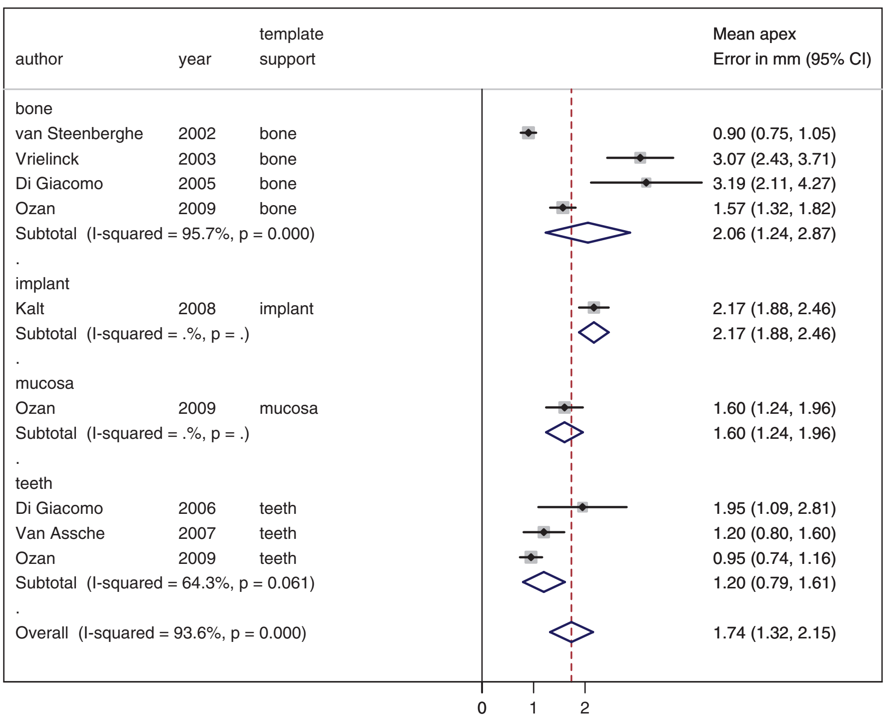

Fig. 11. Deviation at entry point, stratified by template support (bone, implant, mucosa or teeth).

Treatment outcome

Early surgical and prosthetic complications

Eight out of 10 studies reported on clinical complications or unforeseen events during operation or the subsequent early healing period (428 Patients, 1581 implants) (Table 2).

In six out of eight studies 39 early surgical complications have been described (Table 3), corresponding to an early surgical complication rate of 9.1% of the patients or 2.5% of the implant placements. The most frequent problem was a limited access in posterior areas (10 patients, 2.3% of the patients).

In three studies immediate prosthetic restorations were inserted. While in one of these studies no prosthetic complications are described (van Steenberghe et al. 2005), in the other two studies 13 early prosthetic complications (18.8% of the patients) were observed in a total of 69 patients treated with 438 implants. In none of the other five clinical studies prosthetic complications are mentioned. The complications are summarized in Table 4. The most frequent problem was a misfit between the abutment and the prosthesis in five patients (7.3% of the patients).

Late implant failures and prosthetic complications

Reports on implant failures after a minimum observation period of 12 months were found in six out of the 10 included clinical studies (Table 5). From a total of 138 initially treated patients with 721 implants, 79 patients and 587 implants were followed-up for 12–60 months.

In four studies with 101 patients 37 from a total of 537 implants (6.9%) failed during the follow-up period. The implant failure rate in these studies ranged from 4.2% to 9%.

In two studies no implant failures were observed in 10 patients with an unknown number of implants (Fortin et al. 2004) and in 27 patients with 184 implants (van Steenberghe et al. 2005).

The implant failure rate was higher in the one study (Vrielinck et al. 2003) with open flap surgery and delayed loading (8.5%) compared with the four studies with flapless procedures and immediate loading (4.8%).

The occurrence of late prosthetic complications is reported in five studies with 108 patients (Table 5). In two studies no prosthetic complications were encountered, while in the other three studies 13 complications are mentioned (12% of the patients). All prosthetic complications occurred in studies using a flapless procedure with immediate loading.

Discussion

Accuracy

The analysis of the acquired data revealed that the mean horizontal deviation of the described computer-guided systems lies within approximately 1 mm at the entry point and around 1.6 mm at the apex,

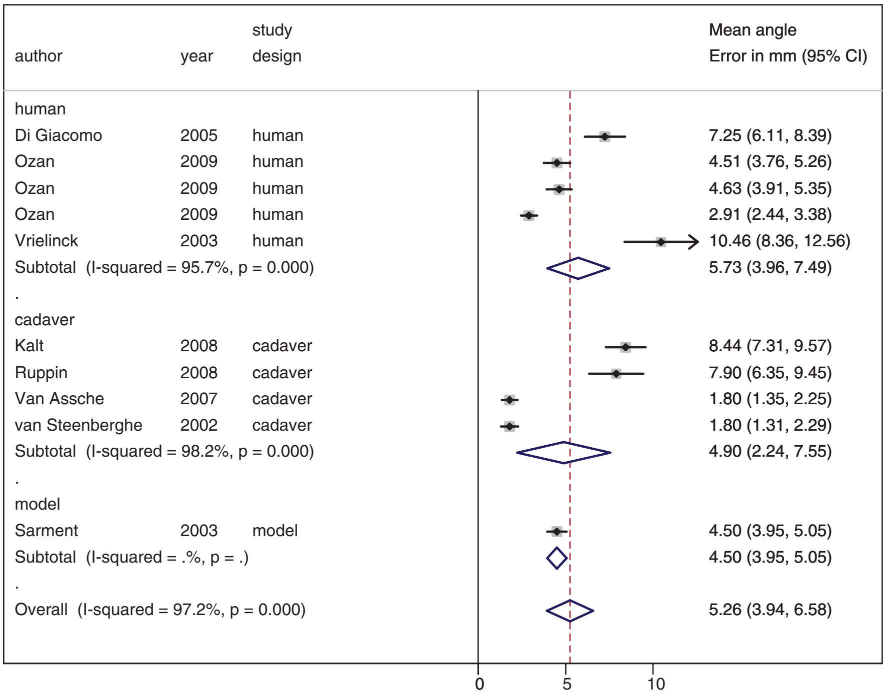

Fig. 12. Deviation in angulation, stratified by study design (human, cadaver or *in vitro* study).

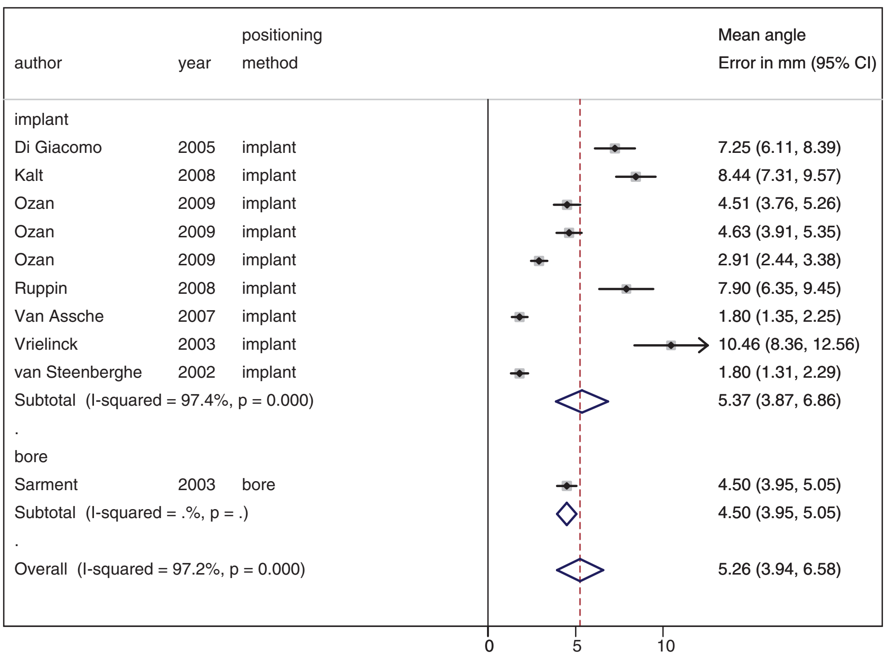

Fig. 13. Deviation in angulation, stratified by positioning method (implants or bore holes).

0.5 mm in height and 5–6° in axis. One problem with the interpretation of the data on accuracy is that the direction of the deviation is not being reported consistently among the studies. While some describe a deviation in horizontal or vertical direction others measure the total deviation in all three dimensions combined.

A large variation of the amount of deviation among the studies, treated patients and even implant sites was observed. Deviations of up to several millimeters were reported. Outliers seem to be a major problem. It seems that the reliability of the computer-guided systems is insufficient to justify a 'blind' implantation. Thus, the diagnostic and surgical procedures require constant verification after each step. Especially in flapless procedures, when visual control is limited, the risk of malpositioning the implant is imminent.

Several possible sources of error during the diagnostic and therapeutic procedure are possible. One of the factors considered to be crucial for precision is the reproducibility and stability of the template position during the CT scan and the implant placement. Based on clinical experience the use of a rigid template material, proper fitting and relining of the template, seating on bone after flap elevation, retention on (temporary) implants or attachment of the surgical guide with auxiliary bone pins are suggested by clinicians to ensure stability of the template. After comparison of the data on deviation the hypothesis that a template supported by bone, teeth or implants provides superior accuracy than a mucosa-supported template, cannot be confirmed. Actually, in one study a proper positioning of the bone-supported template during surgery was prevented by bony interferences Yong & Moy (2008). However, limited data is available for comparison because only one study with mucosal template-support is reported on deviations (Ozan et al. 2009). The same is true regarding the different ways of template production: Only in one study laboratory-fabricated templates were used (Kalt & Gehrke 2008) and no significant differences among the studies regarding deviation dependent on template production were found.

High accuracy of implant placement is required for several reasons. Most important is the avoidance of injury of essential anatomic structures such as nerves, vessels etc. But although a precise transfer of the virtually planned implant position is desirable, a universally valid value in millimeters regarding an 'acceptable' deviation cannot be defined because in some clinical situations even small deviations might be detrimental (e.g. nerve injury) while in other situations an implant malposition can be tolerated and/or compensated. Also, limited data from studies is available for the comparison of accuracy of computer-assisted implant placement with conventional 'free-hand' implantation. In two

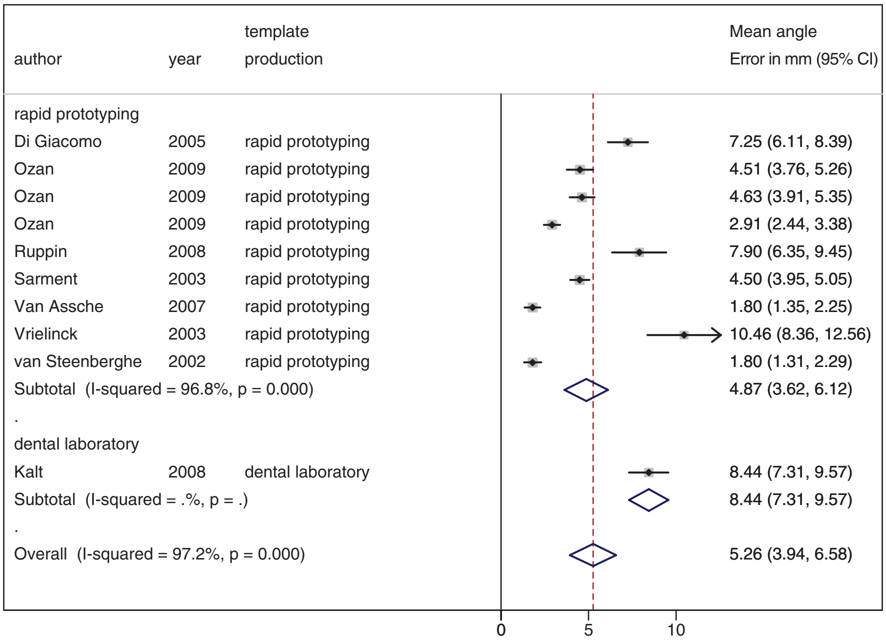

Fig. 14. Deviation in angulation, stratified by template production (rapid prototyping or dental laboratory).

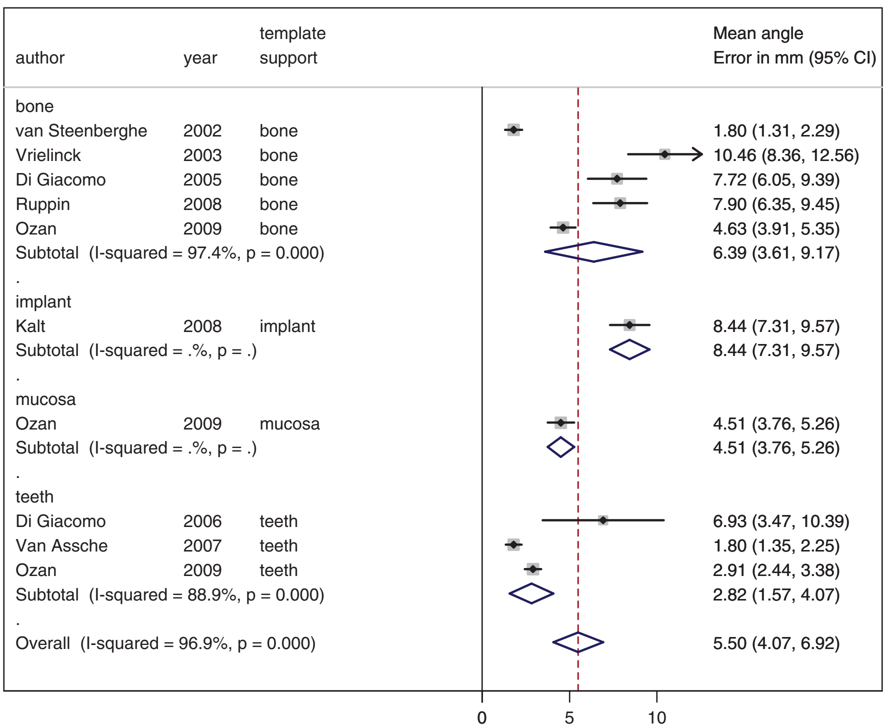

Fig. 15. Deviation in angulation, stratified by template support (bone, implant, mucosa or teeth).

studies, performed on acrylic models, comparing the accuracy of navigation systems with conventional implant preparation revealed a higher precision and reproducibility of placement was found with implants placed by navigation (Brief et al. 2005; Kramer et al. 2005). According to these studies a lateral deviation of approximately 1–1.5 mm and vertical deviation of 1 mm or more must be expected with free-hand drilling in single tooth gaps. No data on accuracy of free-hand drilling or implant placement in partially and completely edentulous patients is available in scientific literature. The amount of mean deviation with free-hand drilling in single-tooth gaps is similar to the results of the present review on computer-guided accuracy including partially and fully edentulous patients.

Clinical performance

Regarding the clinical performance some technology-related problems are mentioned in the analyzed publications (Table 3). Perioperative surgical complications occurred in 9.1% of 428 treated patients. Limited interocclusal distance in posterior segments was the most often-reported complication and occurred in 10 (2.3%) of the treated patients. It can make an insertion of the drills through the surgical template impossible and the implantation procedure cannot be carried out as planned.

Fractures of surgical guides occurred in three cases (0.7%) and underline the need for resistant and rigid materials for template production.

The under- or overestimation of bone volume during CT-data analysis and virtual implant planning seems to reduce the predictability of implant positioning with sufficient implant stability and the need for bone augmentations. In eight patients (1.9%) no implantation was possible and a primary bone augmentation procedure had to be carried out. In three patients (0.7%) an unexpected dehiscence was observed after implant placement. Because investigations on the incidence of bone perforations in flapless procedures are missing computer-guided technology should be used with caution in connection with flapless implant placement. An increase in resolution of CT-data, combined with a reasonable exposure during scanning, might overcome the problem of misinterpretation of the bone volume in the future and contribute to a more predictable and precise implant placement.

Early prosthetic complications are reported in two studies and occurred in 13 of 69 patients (18.8%). All complications were encountered in connection with immediate restoration and prefabricated prostheses. Discrepancies between the planned and actual implant position leading to a misfit of the restoration (7.2%) as well as

Table 2. **Clinical studies reporting on early complications**

No.	Author	Number of patients	Number of implants	Age range	Mean age	System	Template fabrication	Single tooth	Partially edentulous	Completely edentulous	Maxilla	Man-dible	Implant type	Flapless	Open flap	Imme-diate resto-ration	Delayed resto-ration	Number of surgical complica-tions, early	Reason for implant complica-tions, early	Number of prosthetic complica-tions, early	Reason for prosthetic complica-tions, early
1	Fortin et al. (2003)	30	101	18–70	44	CADImplant, Praxim	Dental laboratory	No	Yes	Yes	Yes	Yes	NR	No	Yes	No	Yes	13	6 limited access, 1 implant unstable, 2 implant wider than planned, 1 implant shorter than planned, 3 unexpected dehiscence	NR	NA
2	Komiyama et al. (2008)	29	176	42–90	71.5	NobelGuide, Nobel Biocare	Rapid prototyping	No	No	Yes	Yes	Yes	Nobel Biocare	Yes	No	Yes	No	6	3 fracture of surgical template, 3 infection at drill sites for pins	8	5 misfit of abutment/ bridge (2 disconnec-tions), 3 extensive adjustments of the occlusion
3	Mischkowski et al. (2006)	142	501	NR	NR	Med3D, Med3D GmbH	Dental laboratory	Yes	Yes	Yes	NR	NR	NR	NR	NR	No	Yes	0	NA	NR	NA
		21	78	NR	NR	coDiagnostiX, IVS-Solutions	Dental laboratory	Yes	Yes	Yes	NR	NR	NR	NR	NR	No	Yes	0	NA	NR	NA
		5	32	NR	NR	SimPlant, Materialise	Rapid prototyping	Yes	Yes	Yes	NR	NR	NR	NR	NR	No	Yes	0	NA	NR	NA
4	Nickenig & Eitner (2007)	102	250	22–58	40.4	coDiagnostiX, IVS-Solutions	Dental laboratory	Yes	Yes	Yes	Yes	Yes	NR	Yes	Yes	No	Yes	13	4 limited access, 8 bone augmentation without implant placement, 1 smaller diameter than planned	NR	NA
5	Ozan et al. (2009)	30	110	37–47	47	Stent CAD, Media Lab	Rapid prototyping	NR	Yes	Yes	NR	NR	Zimmer Dental	Yes	Yes	NR	NR	0	NA	NR	NA
6	van Steenberghe et al. (2005)	27	184	34–89	63	NobelGuide, Nobel Biocare	Rapid prototyping	No	No	Yes	Yes	No	Nobel Biocare	Yes	No	Yes	No	1	1 marginal fistula	0	NA
7	Vrielinck et al. (2003)	29	71	37–71	56.4	SurgiGuide, Materialise	Rapid prototyping	No	No	Yes	Yes	No	Nobel Biocare	No	Yes	No	Yes	3	2 acute sinusitis, 1 buccosinusal fistula	NR	NA
8	Yong & Moy (2008)	13	78	NR	67.5	NobelGuide, Nobel Biocare	Rapid prototyping	No	Yes	Yes	Yes	Yes	Nobel	Yes	No	Yes	No	3	1 unsuccessful implant placement in depth, explantation, 1 prolongued pain, 1 soft tissue defect	5	2 incomplete seating of prosthesis due to bony interference, 1 prosthesis loosening, 1 speech problems, 1 cheek biting

NR, not reported; NA, not applicable.

Table 3. **Early surgical complications in a total of 428 treated patients**

Early surgical complication	Number of patients	% of complications	% of patients
Limited access	10	25.6	2.3
Primary bone augmentation necessary	8	20.5	1.9
Unexpected bony dehiscence	3	7.7	0.7
Fracture of template	3	7.7	0.7
Infection at drill sites for pins	3	7.7	0.7
Insertion of wider implant than planned	2	5.1	0.5
Acute sinusitis	2	5.1	0.5
Implant unstable	1	2.6	0.2
Insertion of shorter implant than planned	1	2.6	0.2
Insertion of narrower implant than planned	1	2.6	0.2
Marginal fistula	1	2.6	0.2
Buccosinusal fistula	1	2.6	0.2
Unsuccessful implant placement in depth (explantation)	1	2.6	0.2
Prolonged pain	1	2.6	0.2
Soft tissue defect	1	2.6	0.2
Total	39	100	9.1

Table 4. **Early prosthetic complications in 69 treated patients**

Early prosthetic complication	Number of patients	% of complications	% of patients
Misfit of abutment to bridge	5	38.5	7.2
Extensive adjustments of the occlusion	3	23.1	4.3
Incomplete seating of prosthesis due to bony interference	2	15.4	2.9
Prosthesis loosening	1	7.7	1.4
Speech problems	1	7.7	1.4
Cheek biting	1	7.7	1.4
Total	13	100	18.8

extensive occlusal adjustments (4.3%) are described.

Late prosthetic complications, reported in three studies, occurred in 13 (12%) cases and may be associated with the prosthesis material or improper seating: Fractures of the prostheses (2.8%), of the veneering material (1.9%) and screw loosening (2.8%) are described. The tolerance and effect of specially designed abutments to compensate for a certain amount of deviation between implant and prosthesis position seems to be limited. A higher accuracy and reproducibility of implant position as well as optimization of the prosthetic components and fabrication techniques might allow immediate final restorations in the future. In comparison with a recent review on complications related to not computer-assisted implant rehabilitation (Gervais & Wilson 2007), the incidence of technical complications is higher than in studies included in the present review. The occurrence of technical complications with fixed, implant-supported prostheses includes fractures of the prostheses in 3%, acrylic veneer fracture in 22%, ceramic veneer fracture in 14% and fractures or loosening of abutment or prostheses screws in 17% of the prostheses. Because of the different prosthesis designs, loading protocols, observation periods and since a generally accepted definition of a prosthetic or surgical complication is inexistent and therefore unforeseen events may not always be reported, the data must be interpreted and with caution.

After a follow-up of 12–60 months an implant survival rate of 91–100% was reported in a total of six studies with 79 patients and 587 implants. Keeping in mind that in four out of six studies implants were inserted in fully edentulous patients and immediately loaded the implant failure rates are similar to conventional procedures (Pjetursson et al. 2004; Esposito et al. 2007). However, due to the relatively short observation period and low variety of systems used, further investigations are necessary to confirm the high long-term implant survival.

Conclusions

Based on the data analysis of this systematic review it is concluded that various systems for computer-guided template-based implant treatment are available. Different types of software, template production and template stabilization as well as variations of the surgical and prosthetic protocol are reported. Meta-analysis of *in vitro*, cadaver and clinical studies regarding accuracy revealed mean horizontal deviations of 1.1–1.6 mm, but also considerably higher maximum deviations. The survival rate of implants placed with computer-guided technology is comparable to conventionally placed implants ranging from 91% to 100% after an observation time of 12–60 months. Early surgical complications were observed in 9.1%, early prosthetic complications in 18.8% and late prosthetic complications in 12% of the patients. However, limited data and relatively short observation periods are available in literature. Further research should involve clinical studies with long-term follow-up and strive for an improvement of the systems and procedures regarding accuracy, predictability and reproducibility of implant placement as well as surgical and prosthetic outcomes.

Table 5. **Late implant and prosthetic complications**

No	Author	Number of patients	Number of implants	Age range	Mean age	Mean follow-up (month)	Follow-up range (month)	System	Template fabrication	Single tooth	Partially edentulous	Completely edentulous	Maxilla	Mandible	Implant type	Flapless	Open flap	Immediate restoration	Delayed restoration	Number of implant complications, late	Reason for implant complication, late	Number of prosthetic complications, late	Reason for prosthetic complications, late
1	Fortin et al. (2004)	10	NR	NR	NR	12	NR	CADImplant, Praxim	Dental laboratory	No	No	Yes	NR	NR	NR	No	Yes	Yes	Yes	0	NA	0	NA
2	Komiyama et al. (2008)	29	176	42–90	71.5	NR	12–44	Nobel-Guide, Nobel Biocare	Rapid prototyping	No	No	Yes	Yes	yes	Nobel Biocare	Yes	No	Yes	No	15	15 implant failure	1	1 replacement of suprastructure due to misfit
3	Sanna et al. (2007)	30	212	38–74	56	26.4	Up to 60	Nobel-Guide, Nobel Biocare	Rapid prototyping	No	No	Yes	NR	NR	Nobel Biocare	Yes	No	Yes	No	9	9 implant failure	NR	NA
4	van Steenberghe et al. (2005)	27	184	34–89	63	12	NR	Nobel-Guide, Nobel Biocare	Rapid prototyping	No	No	Yes	Yes	no	Nobel Biocare	Yes	No	Yes	No	0	NA	3	1 screw loosening, 2 occlusal material fracture
5	Vrielinck et al. (2003)	29	71	37–71	56.4	14	NR	Surgi-Guide, Materialise	Rapid prototyping	No	No	Yes	Yes	no	Nobel Biocare	No	Yes	No	Yes	6	6 implant failure	0	NA
6	Yong & Moy (2008)	13	78	NR	67.5	26.6	NR	Nobel-Guide, Nobel Biocare	Rapid prototyping	No	Yes	Yes	Yes	yes	Nobel	Yes	No	Yes	No	7	7 implant failure	9	2 occlusal wear, 2 screw loosening, 3 prosthesis fracture, 1 esthetic dissatisfaction, 1 pressure sensitivity

NR, not reported; NA, not applicable.

Table 6. **Late prosthetic complications**

Late prosthetic complication	Number of patients	% of complications	% of patients
Screw loosening	3	23.1	2.8
Prosthesis fracture	3	23.1	2.8
Occlusal material fracture	2	15.4	1.9
Occlusal wear	2	15.4	1.9
Suprastructural misfit	1	7.7	0.9
Esthetic dissatisfaction	1	7.7	0.9
Pressure sensitivity	1	7.7	0.9
Total	13	100	12

Table 7. **List of excluded abstracts and full text articles**

Publication	Reason for exclusion
Abbo, B., Miller, S. E. (2008) Endosseous implants and immediate provisionalization in the aesthetic zone: computer-guided surgery. *Dentistry Today* 27, 88, 90, 92.	Method
Allum, S. R. (2008) Immediately loaded full-arch provisional implant restorations using CAD/CAM and guided placement: maxillary and mandibular case reports. *British Dentistry Journal* **204**: 377–81.	Unavailable
Azari, A., Nikzad, S. (2008) Flapless implant surgery: review of the literature and report of 2 cases with computer-guided surgical approach. *Journal of Oral Maxillofacial Surgery* **66**: 1015–21.	Case report
Balshi, T. J., Balshi, S. F.: Jaffin, R, Salama, M. A., Triplett, R. G., Parel S. (2008) CT-generated surgical guides and flapless surgery. *The International Journal of Oral & Maxillofacial Implants* **23**: 190–7.	Unavailable
Balshi, S.F., Wolfinger, G.J., Balshi, T.J. (2008) Guided implant placement and immediate prosthesis delivery using traditional Branemark System abutments: a pilot study of 23 patients. *Implant Dentistry* **17**: 128–35.	Unavailable
Bousquet, F., Joyard, M. (2008) Surgical navigation for implant placement using transtomography. *Clinical Oral Implants Research* **19**: 724–30.	Navigation
Buser, D., Chen, S. T., Weber, H. P., Belser, U. C. (2008) Early implant placement following single-tooth extraction in the esthetic zone: biologic rationale and surgical procedures. *International Journal of Periodontics and Restorative Dentistry* **28**: 441–51.	Navigation
Carrick, J. L., Freedman, G. (2008) Implants in the 21st century – computer guided surgery. *Dentistry Today* 27, 80, 82, 84–5 passim.	Review
Casap, N., Wexler, A., Eliashar, R. (2008) Computerized navigation for surgery of the lower jaw: comparison of 2 navigation systems. *Journal of Oral and Maxillofacial Surgery* **66**: 1467–75.	Navigation
Cheng, A. C., Tee-Khin, N., Siew-Luen, C., Lee, H., Wee, A. G. (2008) The management of a severely resorbed edentulous maxilla using a bone graft and a CAD/CAM-guided immediately loaded definitive implant prosthesis: a clinical report. *Journal of Prosthetic Dentistry* **99**: 85–90.	Case report
Ersoy, A. E., Turkyilmaz, I., Ozan, O., McGlumphy, E. A. (2008) Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *Journal of Periodontology* **79**: 1339–45.	Redundant patient data
Hariharan, R., Rajan, M. (2008) A modified dental implant surgical template for the prevention of flap interference in a completely edentulous maxilla. *Journal of Prosthetic Dentistry* **100**: 410–1.	Navigation
Heiland, M., Pohlenz, P., Blessman, M., Werle, H., Fraederich, M., Schmelzle., R., Blake, F. A. (2008) Navigated implantation after microsurgical bone transfer using intraoperatively acquired cone-beam computed tomography data sets. *The International Journal of Oral and Maxillofacial Surgery* **37**: 70–5.	Navigation
Jayme, S. J., Muglia, V. A., de Oliveira, R. R., Novaes, A. B. (2008) Optimization in multi-implant placement for immediate loading in edentulous arches using a modified surgical template and prototyping: a case report. *International Journal of Oral & Maxillofacial Implants* **23**: 759–62.	Case report
Katsoulis, J., Pazera, P., Mericske-Stern, R. (2008) Prosthetically driven, computer-guided implant planning for the edentulous maxilla: a model study. *Clinical Implant Dentistry & Related Research*. Epub ahead of print.	Not subject related
Mandelaris, G. A., Rosenfeld, A. L. (2008) The expanding influence of computed tomography and the application of computer-guided implantology. *Practical Procedures in Aesthetic Dentistry* **20**: 297–305; quiz 306.	Review
Nikzad, S., Azari, A. (2008) A novel stereolithographic surgical guide template for planning treatment involving a mandibular dental implant. *Journal of Oral and Maxillofacial Surgery* **66**: 1446–54.	Case report
Papaspyridakos, P., Lal, K. (2008) Flapless implant placement: a technique to eliminate the need for a removable interim prosthesis. *Journal of Prosthetic Dentistry* **100**: 232–5.	Case report
Penarrocha, M., Boronat, A., Carrillo, C., Albalat, S. (2008) Computer-guided implant placement in a patient with severe atrophy. Journal of Oral Implantology **34**: 203–7.	Case report
Suzuki, E. Y., Suzuki, B. (2008) Accuracy of miniscrew implant placement with a 3-dimensional surgical guide. *Journal of Oral and Maxillofacial Surgery* **66**: 1245–52.	Not subject related
Tee-Khin, N., Cheng, A. C., Lee, H., Wee, A. G., Leong, E. W. (2008) The management of a completely edentulous patient using simultaneous maxillary and mandibular CAD/CAM-guided immediately loaded definitive implant-supported prostheses: a clinical report. *Journal of Prosthetic Dentistry* **99**: 416–20.	Case report
van der Zel, J. M. (2008) Implant planning and placement using optical scanning and cone beam CT technology. Journal of Prosthodontics **17**: 476–81.	Method
Vercruyssen, M., Jacobs, R., Van Assche, N., van Steenberghe, D. (2008) The use of CT scan based planning for oral rehabilitation by means of implants and its transfer to the surgical field: a critical review on accuracy. *Journal of Oral Rehabilitation* **35**, 454–74.	Review
Wat, P. Y., Pow, E. H., Chau, F. S., Leung, K. C. (2008) A surgical guide for dental implant placement in an edentulous jaw. *Journal of Prosthetic Dentistry* **100**: 323–5.	Navigation
Widmann, G., Widmann, R., Widmann, E., Jaschke, W., Bale, R. (2007) Use of a surgical navigation system for CT-guided template production. *The International Journal of Oral & Maxillofacial Implants* **22**: 72–78.	Navigation

References

Brief, J., Edinger, D., Hassfeld, S. & Eggers, G. (2005) Accuracy of image-guided implantology. *Clinical Oral Implants Research* **16**: 495–501.

Di Giacomo, G.A., Cury, P.R., de Araujo, N.S., Sendyk, W.R. & Sendyk, C.L. (2005) Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *Journal of Periodontology* **76**: 503–507.

Esposito, M., Grusovin, M.G., Willings, M., Coulthard, P. & Worthington, H.V. (2007) The effectiveness of immediate, early, and conventional loading of dental implants: a cochrane systematic review of randomized controlled clinical trials. *The International Journal of Oral & Maxillofacial Implants* **22**: 893–904.

Fortin, T., Bosson, J.L., Coudert, J.L. & Isidori, M. (2003) Reliability of preoperative planning of an image-guided system for oral implant placement based on 3-dimensional images: an in vivo study. *The International Journal of Oral & Maxillofacial Implants* **18**: 886–893.

Fortin, T., Isidori, M., Blanchet, E., Perriat, M., Bouchet, H. & Coudert, J.L. (2004) An image-guided system-drilled surgical template and trephine guide pin to make treatment of completely edentulous patients easier: a clinical report on immediate loading. *Clinical Implant Dentistry & Related Research* **6**: 111–119.

Gervais, M.J. & Wilson, P.R. (2007) A rationale for retrievability of fixed, implant-supported prostheses: a complication-based analysis. *International Journal of Prosthodontics* **20**: 13–24.

Guerrero, M.E., Jacobs, R., Loubele, M., Schutyser, F., Suetens, P. & van Steenberghe, D. (2006) State-of-the-art on cone beam ct imaging for preoperative planning of implant placement. *Clinical Oral Investigations* **10**: 1–7.

Hammerle, C.H., Jung, R.E. & Feloutzis, A. (2002) A systematic review of the survival of implants in bone sites augmented with barrier membranes (guided bone regeneration) in partially edentulous patients. *Journal of Clinical Periodontology* **29** (Suppl. 3): 226–231; discussion 232–223.

Higgins, J.P. & Thompson, S.G. (2002) Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine* **21**: 1539–1558.

Jung, R.E., Pjetursson, B.E., Glauser, R., Zembic, A., Zwahlen, M. & Lang, N.P. (2008) A systematic review of the 5-year survival and complication rates of implant-supported single crowns. *Clinical Oral Implants Research* **19**: 119–130.

Jung, R.E., Schneider, D., Ganeles, J., Wismeijer, D., Zwahlen, M., Hammerle, C.H.F. & Tahmaseb, A. (in press) Computer technology applications in surgical implant dentistry – a systematic review. *The International Journal of Oral & Maxillofacial Implants*.

Kalt, G. & Gehrke, P. (2008) Transfer precision of three-dimensional implant planning with ct assisted offline navigation. *International Journal of Computerized Dentistry* **11**: 213–225.

Komiyama, A., Klinge, B. & Hultin, M. (2008) Treatment outcome of immediately loaded implants installed in edentulous jaws following computer-assisted virtual treatment planning and flapless surgery. *Clinical Oral Implants Research* **19**: 677–685.

Kramer, F.J., Baethge, C., Swennen, G. & Rosahl, S. (2005) Navigated vs. Conventional implant insertion for maxillary single tooth replacement. *Clinical Oral Implants Research* **16**: 60–68.

Mischkowski, R.A., Zinser, M.J., Neugebauer, J., Kubler, A.C. & Zoller, J.E. (2006) Comparison of static and dynamic computer-assisted guidance methods in implantology. *International Journal of Computerized Dentistry* **9**: 23–35.

Nickenig, H.J. & Eitner, S. (2007) Reliability of implant placement after virtual planning of implant positions using cone beam ct data and surgical (guide) templates. *Journal of Craniomaxillofacial Surgery* **35**: 207–211.

Ozan, O., Turkyilmaz, I., Ersoy, A.E., McGlumphy, E.A. & Rosenstiel, S.F. (2009) Clinical accuracy of 3 different types of computed tomography-derived stereolithographic surgical guides in implant placement. *Journal of Oral and Maxillofacial Surgery* **67**: 394–401.

Pjetursson, B.E., Bragger, U., Lang, N.P. & Zwahlen, M. (2007) Comparison of survival and complication rates of tooth-supported fixed dental prostheses (fdps) and implant-supported fdps and single crowns (scs). *Clinical Oral Implants Research* **18** (Suppl. 3): 97–113.

Pjetursson, B.E., Tan, K., Lang, N.P., Bragger, U., Egger, M. & Zwahlen, M. (2004) A systematic review of the survival and complication rates of fixed partial dentures (fpds) after an observation period of at least 5 years. *Clinical Oral Implants Research* **15**: 625–642.

Ruppin, J., Popovic, A., Strauss, M., Spuntrup, E., Steiner, A. & Stoll, C. (2008) Evaluation of the accuracy of three different computer-aided surgery systems in dental implantology: optical tracking vs. Stereolithographic splint systems. *Clinical Oral Implants Research* **19**: 709–716.

Sanna, A.M., Molly, L. & van Steenberghe, D. (2007) Immediately loaded cad-cam manufactured fixed complete dentures using flapless implant placement procedures: a cohort study of consecutive patients. *Journal of Prosthetic Dentistry* **97**: 331–339.

Sarment, D.P., Sukovic, P. & Clinthorne, N. (2003) Accuracy of implant placement with a stereolithographic surgical guide. *The International Journal of Oral & Maxillofacial Implants* **18**: 571–577.

Schulze, D., Heiland, M., Thurmann, H. & Adam, G. (2004) Radiation exposure during midfacial imaging using 4- and 16-slice computed tomography, cone beam computed tomography systems and conventional radiography. *Dentomaxillofacial Radiology* **33**: 83–86.

Van Assche, N., van Steenberghe, D., Guerrero, M.E., Hirsch, E., Schutyser, F., Quirynen, M. & Jacobs, R. (2007) Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: a pilot study. *Journal of Clinical Periodontology* **34**: 816–821.

van Steenberghe, D., Glauser, R., Blomback, U., Andersson, M., Schutyser, F., Pettersson, A. & Wendelhag, I. (2005) A computed tomographic scan-derived customized surgical template and fixed prosthesis for flapless surgery and immediate loading of implants in fully edentulous maxillae: a prospective multicenter study. *Clinical Implant Dentistry & Related Research* **7** (Suppl. 1): S111–S120.

van Steenberghe, D., Naert, I., Andersson, M., Brajnovic, I., Van Cleynenbreugel, J. & Suetens, P. (2002) A custom template and definitive prosthesis allowing immediate implant loading in the maxilla: a clinical report. *The International Journal of Oral & Maxillofacial Implants* **17**: 663–670.

Vrielinck, L., Politis, C., Schepers, S., Pauwels, M. & Naert, I. (2003) Image-based planning and clinical validation of zygoma and pterygoid implant placement in patients with severe bone atrophy using customized drill guides. Preliminary results from a prospective clinical follow-up study. *The International Journal of Oral and Maxillofacial Surgery* **32**: 7–14.

Yong, L.T. & Moy, P.K. (2008) Complications of computer-aided-design/computer-aided-machining-guided (nobelguidetrade mark) surgical implant placement: an evaluation of early clinical results. *Clinical Implant Dentistry & Related Research* **10**: 123–127.