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Abstract

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A systematic review on the accuracy and the clinical outcome of computer-guided template based implant dentistry. EAO Consensus Conference 2009, Group 2

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Key words:
dental implants, computer-guided implant dentistry, 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, 8 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: 1.26-2.00 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% to 100% after an observation time of 12 to 60 months are reported in 6 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.

Introduction

Prosthetic rehabilitation with implant-supported prostheses is considered to be a routine procedure with high success rates (Jung et al. 2008; Hammerle et al. 2002; Pjetursson et al. 2007). Prior to 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 preoperative planning the third dimension of the patient's anatomy is missing. Although in medicine computer tomography has been providing tree-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 due to 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 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 CAD-CAM technology. Other systems use intraoperative optical tracking of the hand-piece position with cameras and guide the surgeon "real-time" providing visual feedback on a screen. The later 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 (Komiyama et al. 2008; Sanna et al. 2007; van Steenberghe et al. 2005) . 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, since 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 (Figure 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 borehole deviations were included.

For studies on ***clinical performance*** no restrictions were made regarding the study design but only studies with a minimum of 5 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 the present systematic review. Studies using “dynamic“ 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 5 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 (Figure 2): Accuracy and clinical performance. For ***accuracy***, the following four parameters were evaluated (Figure 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: $se = sd/\sqrt{n}$, 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, 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 3 accuracy and 2 clinical studies were additionally included for this review (Figures 1 + 2, Table 7).

After merging with the already acquired articles from 1966 to December 2007 (Jung et al. in press) a total of 8 articles reporting on accuracy and 10 clinical studies on computer guided, template based implant insertion were available for this systematic review (Figure 1).

Accuracy studies

In 8 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), 4 on cadavers (116 implantation sites) and 3 in humans (155 implant sites). A total of 321 sites were analyzed, 50 of which were boreholes and 271 implants. 4 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.

Error at entry point and apex

The over all mean error at the entry point (8 studies, 321 sites) was 1.07 mm (95% CI: 0.76-1.22 mm) and at the apex (7 studies, 281 sites) 1.63 mm (95% CI: 1.26-2.00 mm).

At the entry point the mean deviation was similar in studies performed in humans (3 studies, 155 sites) (1.16 mm, 95% CI: 0.92-1.39 mm), cadavers (4 studies, 116 sites) (1.04 mm, 95% CI: 0.74-1.34 mm) and models (1 study, 50 sites) (0.90 mm, 95% CI: 0.76-1.04 mm) (Figure 4). At the apex the mean deviation was 1.96 mm (95% CI: 1.33-2.58 mm) in studies performed in humans (3 studies, 155 sites), 1.42 mm (95% CI: 0.59-2.25 mm) in cadavers (3 studies, 76 sites) and 1.00 mm (95% CI: 0.83-1.17 mm) in models (1 study, 50 sites) (Figure 8).

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 (7 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 1.00 (95% CI: 0.83-1.17 mm) at the apex (Figures 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 (7 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 (Figures 6 and 10).

Surgical templates supported by teeth (3 studies, 46 sites), bone (5 studies, 144 sites) or implants (1 study, 48 implants) (Kalt & Gehrke 2008) did not show a significantly different accuracy, neither at the entry point nor at the apex compared to mucosa-supported templates (1 study, 30 sites) (Ozan et al. 2009) (Figures 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 2 studies (88 sites), both performed with implants on cadavers. The mean error in height for the 2 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).

Error in angulation

Information about the deviation in angulations was found in 8 studies (321 sites). The over all mean error in angulation was 5.26° (95% CI: 3.94-6.58°). In 3 clinical studies (155 sites) the mean error in angulation was 5.73° (95% CI: 3.96-7.49°), in 4 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°)(Figure 12). In one study with 50 boreholes (Sarment et al. 2003) the mean error was 4.5° (95% CI: 3.95-5.05°), in 7 studies with implants (271 sites) 5.37° (95% CI: 3.87-6.86°) (Figure 13). Laboratory fabricated guides (1 study, 48 sites) showed a mean error of 8.44° (95% CI: 7.31-9.57°), stereolithographically fabricated guides (7 studies, 753 sites) 4.87° (95% CI: 3.62-6.12°)(Figure 14).

For teeth supported guides (3 studies, 46 sites) the mean deviation was 2.82° (95% CI: 1.57-4.07°), for bone supported guides (5 studies, 144 sites) 6.39° (95% CI: 3.61-9.17°), for implant supported guides (1 study, 48 sites) 8.44° (95% CI: 7.31-9.57°) and for mucosa supported (1 study, 30 sites) 4.51° (95% CI: 3.76-5.26°).

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

10 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. 9 studies reported on the treatment of completely edentulous cases, 5 studies of partially edentulous cases. In 6 out of 10 studies flapless implantation procedures were performed, in 4 studies in combination with an immediate restoration.

6 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 7 out of 10 studies stereolithographically produced surgical templates (rapid prototyping) including 163 patients and 863 implants were used. In 4 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).

Treatment outcome

Early surgical and prosthetic complications

8 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 6 out of 8 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 3 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 5 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 5 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 6 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 to 60 months.
In 4 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 to the 4 studies with flapless procedures and immediate loading (4.8%).

The occurrence of late prosthetic complications is reported in 5 studies with 108 patients (Table 5). In 2 studies no prosthetic complications were encountered, while in the other 3 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 millimeter at the entry point and around 1.6 millimeters at the apex, 0.5 millimeters in height and 5 to 6 degrees 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 2008). However, limited data is available for comparison since only one study with mucosal template-support 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 since 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 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 (Kramer et al. 2005; Brief et al. 2005). According to these studies a lateral deviation of approximately 1 to 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). Peri-operative 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 3 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 8 patients (1.9%) no implantation was possible and a primary bone augmentation procedure had to be carried out. In 3 patients (0.7%) an unexpected dehiscence was observed after implant placement. Since 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 2 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 extensive occlusal adjustments (4.3%) are described.

Late prosthetic complications, reported in 3 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. Due to 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 to 60 months an implant survival rate of 91% to 100% was reported in a total of 6 studies with 79 patients and 587 implants. Keeping in mind that in 4 out of 6 studies implants were inserted in fully edentulous patients and immediately loaded the implant failure rates are similar to conventional procedures (Esposito et al. 2007; Pjetursson et al. 2004). However, due to the relatively short observation period and low variety of systems used, further investigations are necessary 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 mm to 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 to 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.

Figures and Tables

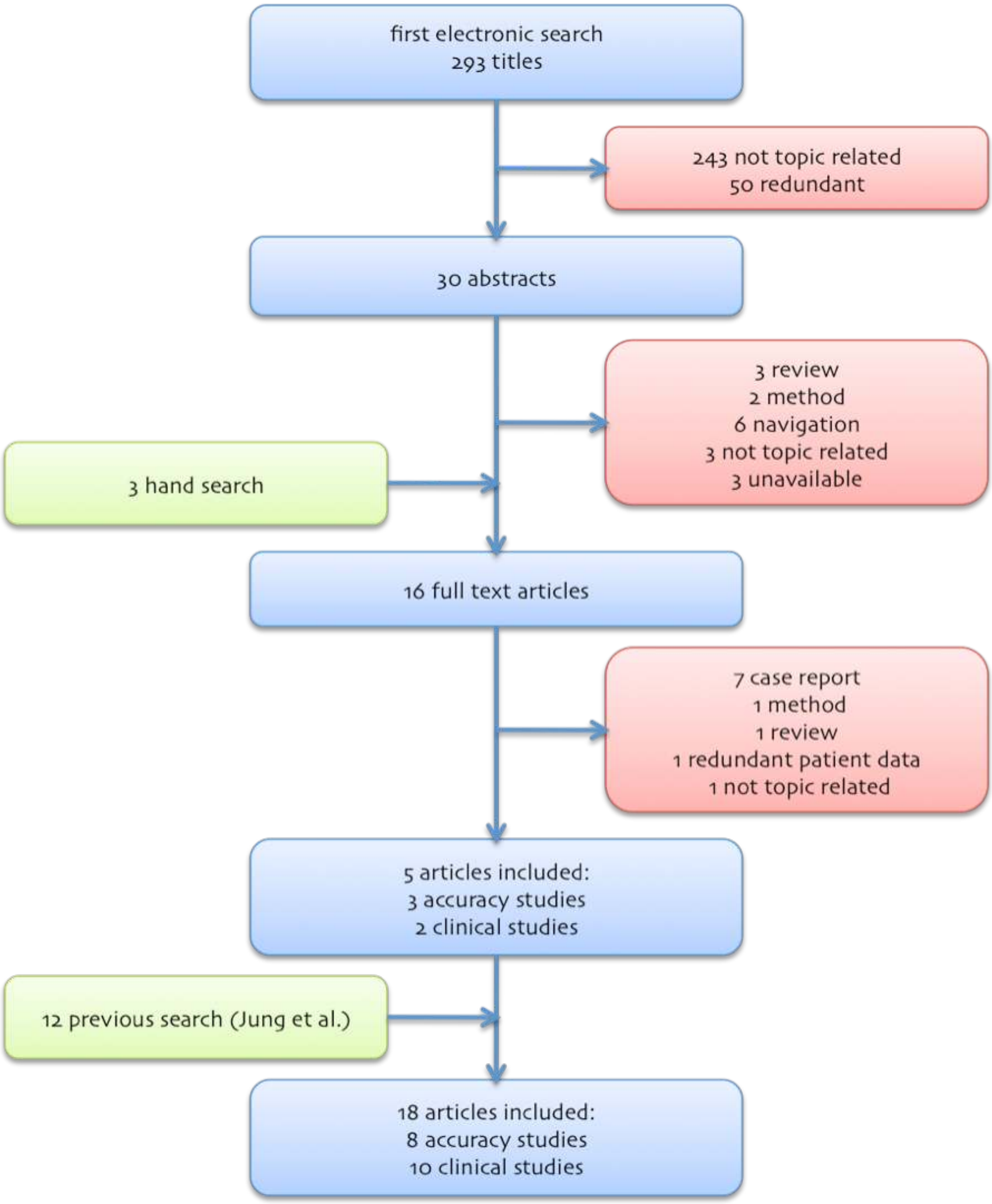

Figure 1: Literature search and article selection

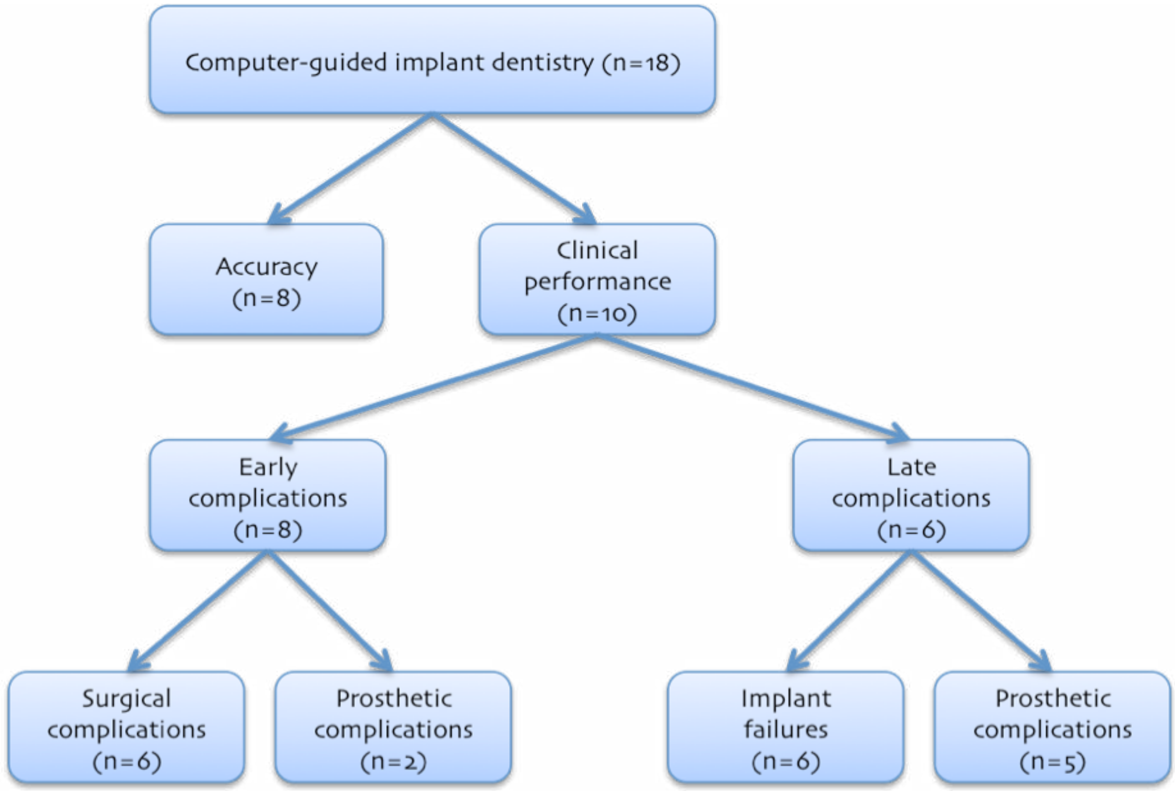

Figure 2: Distribution of studies according to outcome measures

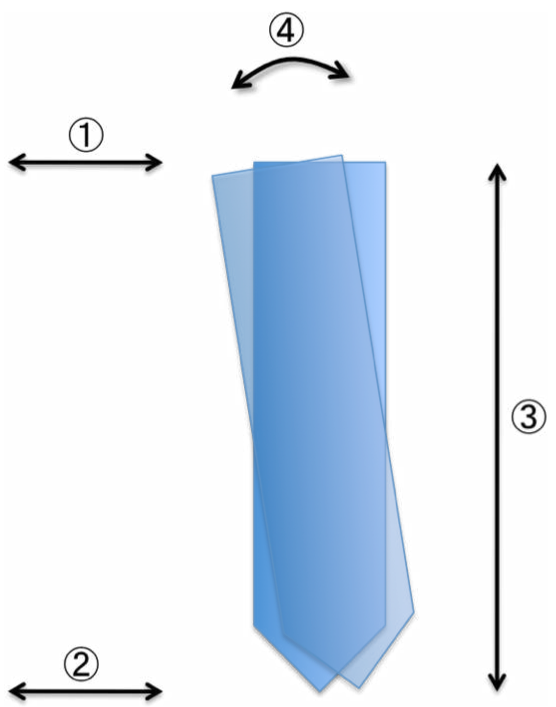

Figure 3: Direction of deviations in the variable "accuracy". 1. Deviation at entry point, 2. deviation at apex, 3. deviation in height and 4. angular deviation.

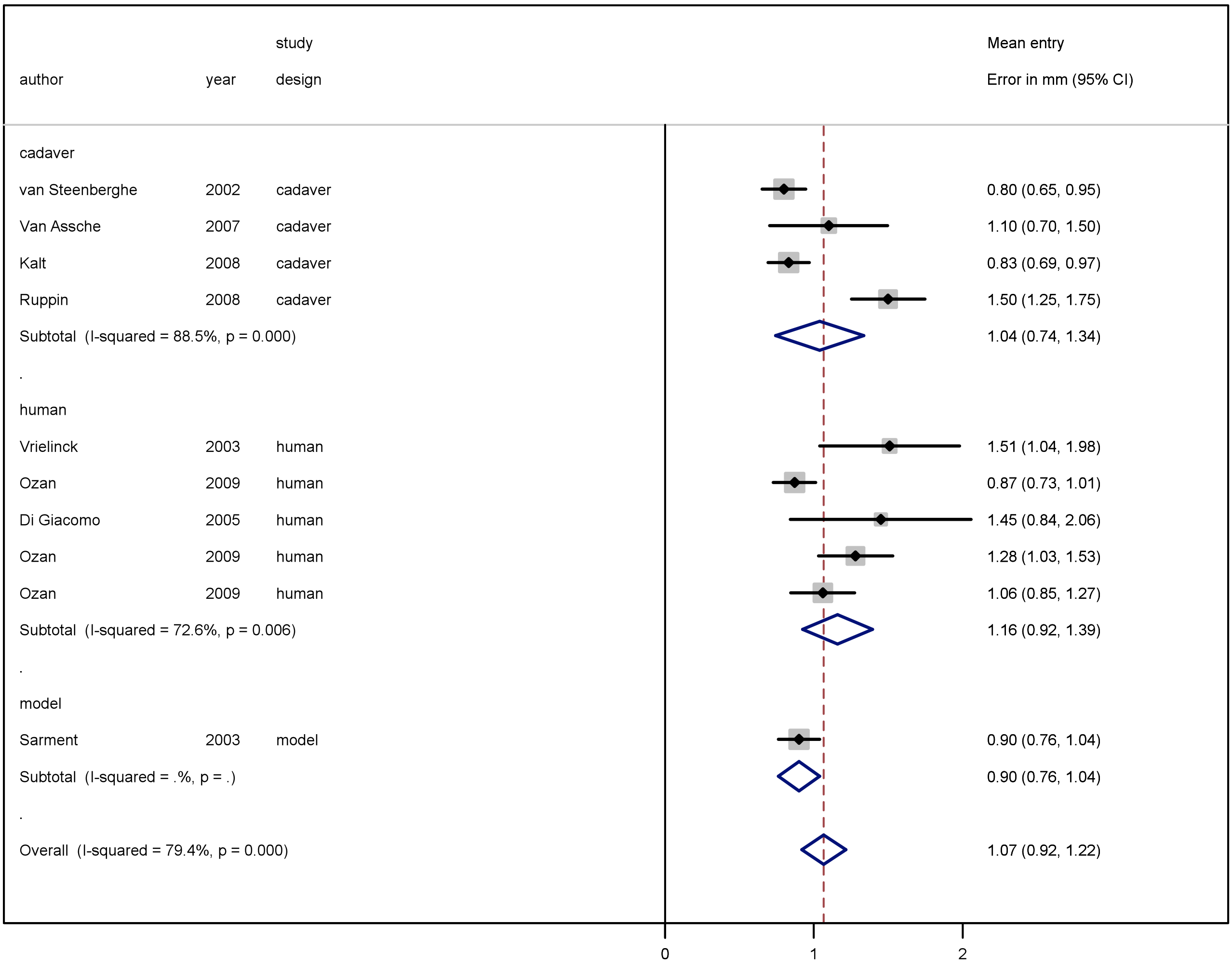

Figure 4: Deviation at entry point, stratified by study design (human, cadaver or on-vitro study)

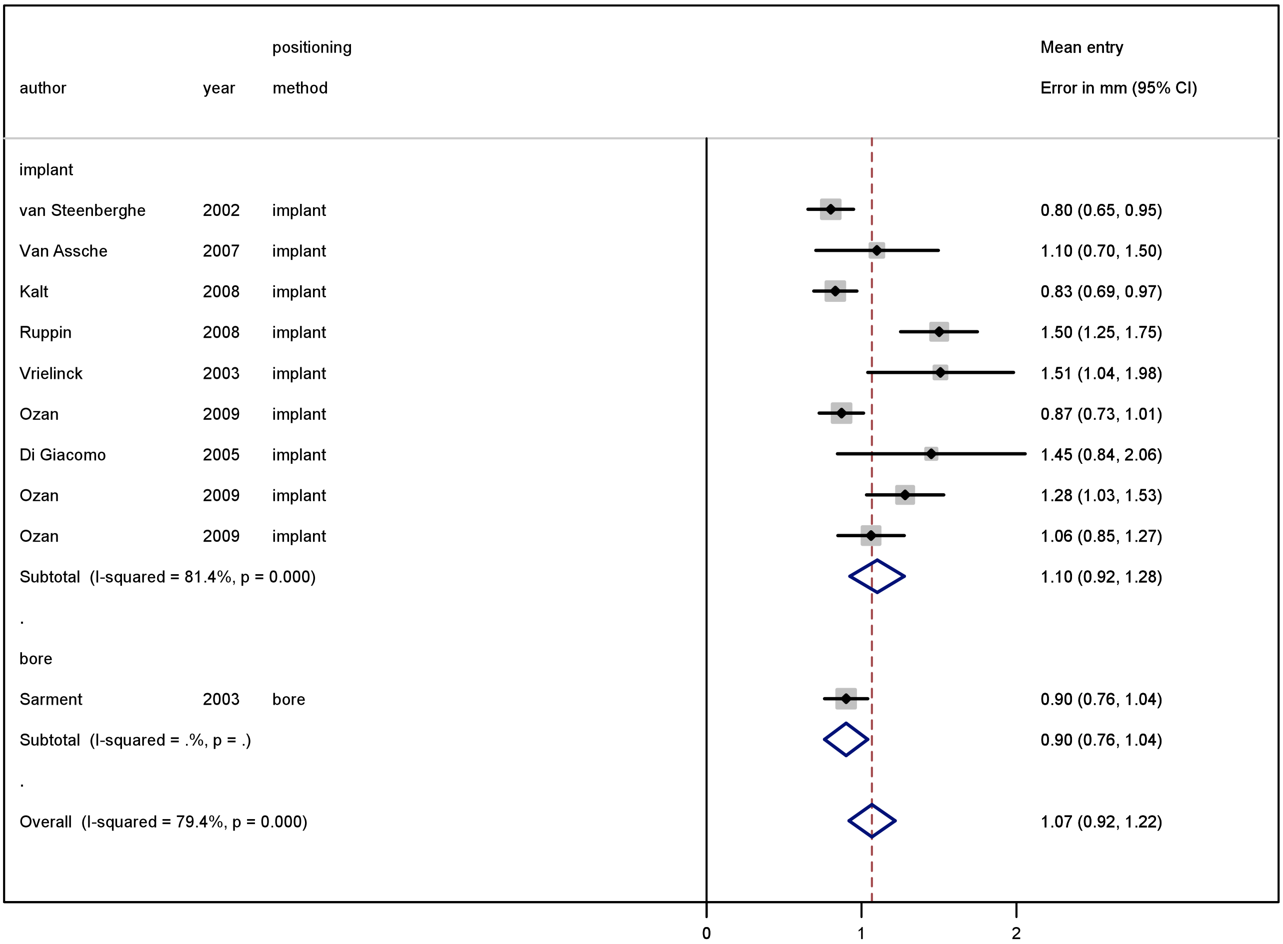

Figure 5: Deviation at entry point, stratified by positioning method (implants or bore holes)

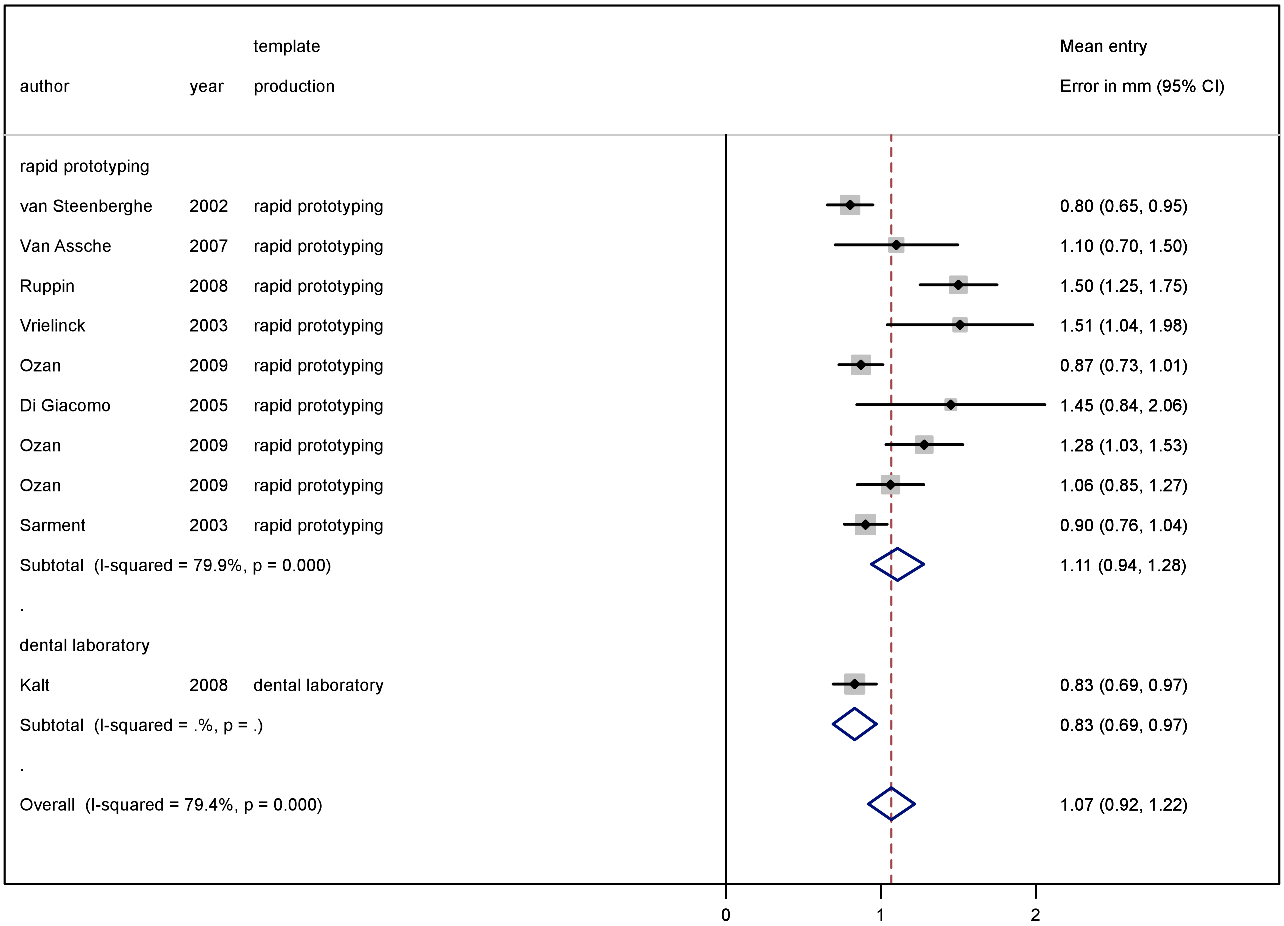

Figure 6: Deviation at entry point, stratified by template production (rapid prototyping or dental laboratory)

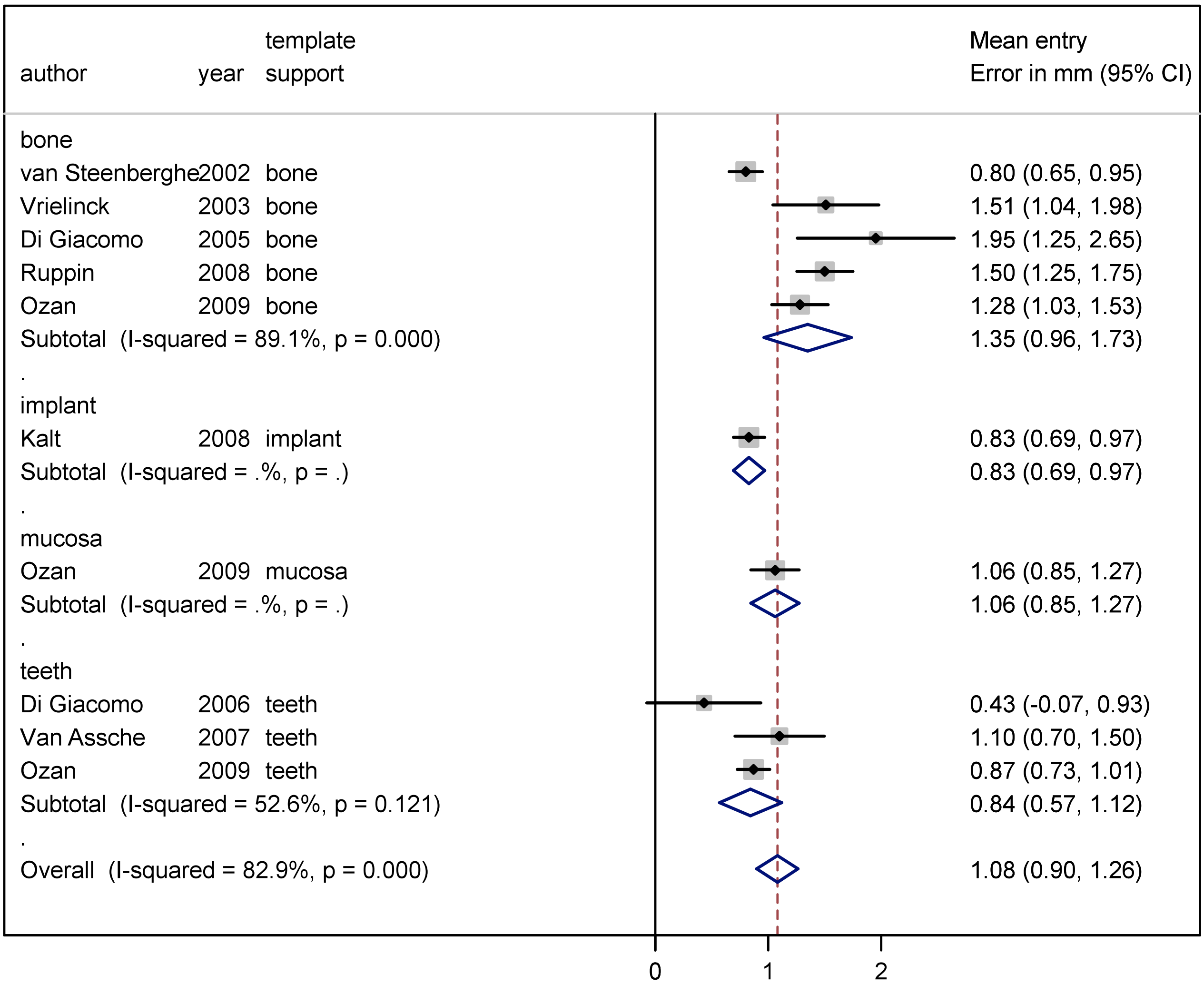

Figure 7: Deviation at entry point, stratified by template support (bone, implant, mucosa or teeth)

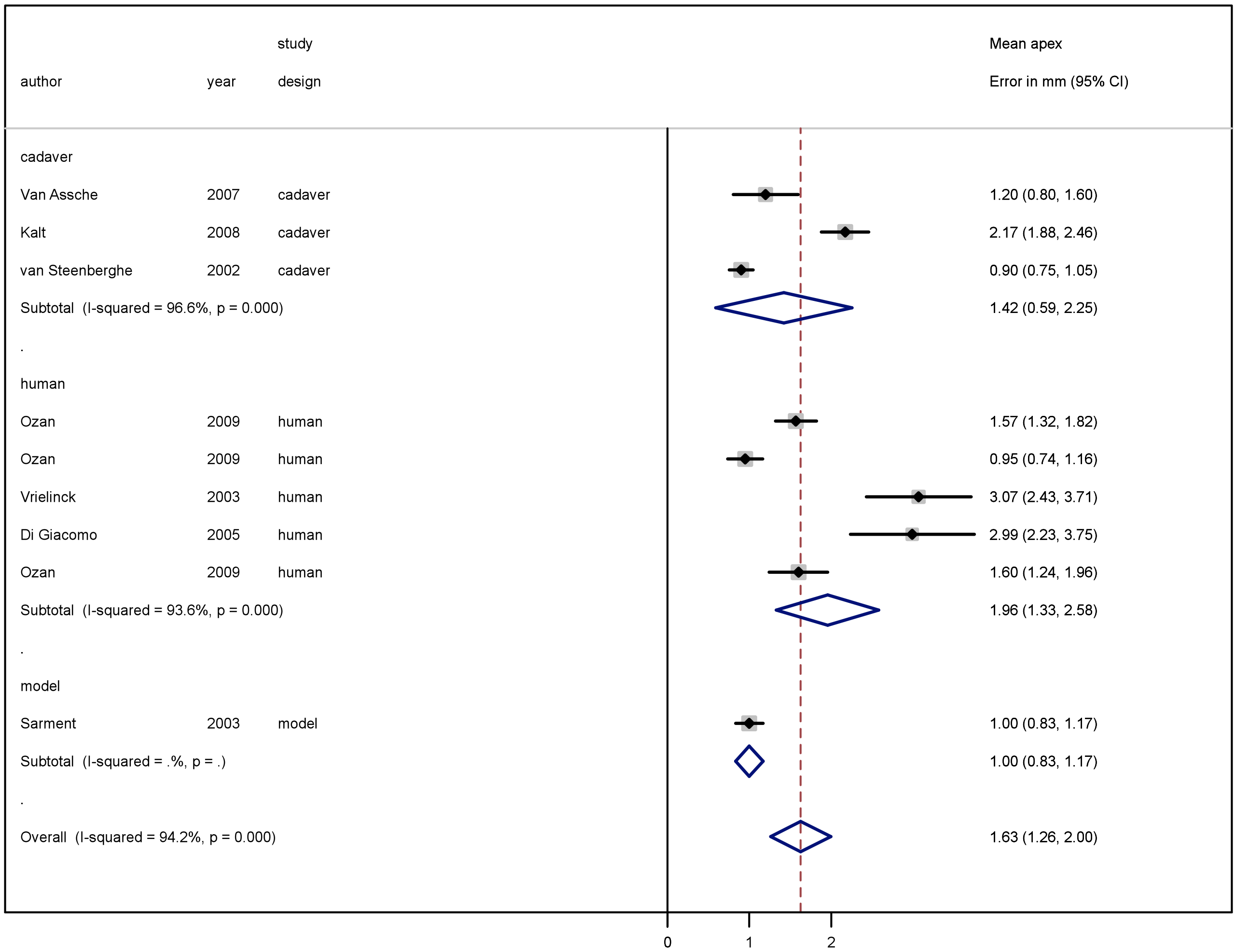

Figure 8: Deviation at apex, stratified by study design (human, cadaver or on-vitro study)

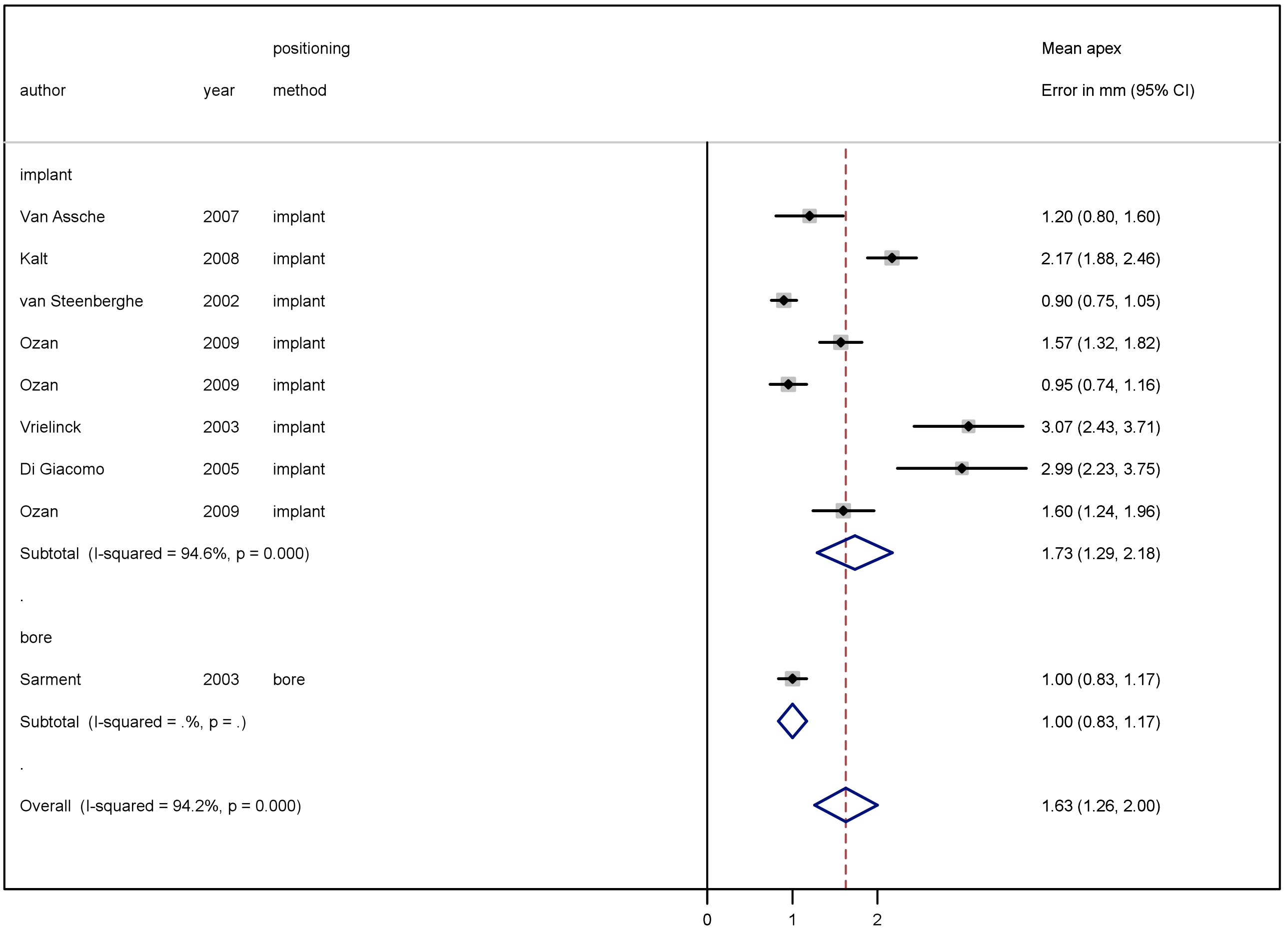

Figure 9: Deviation at entry point, stratified by positioning method (implants or bore holes)

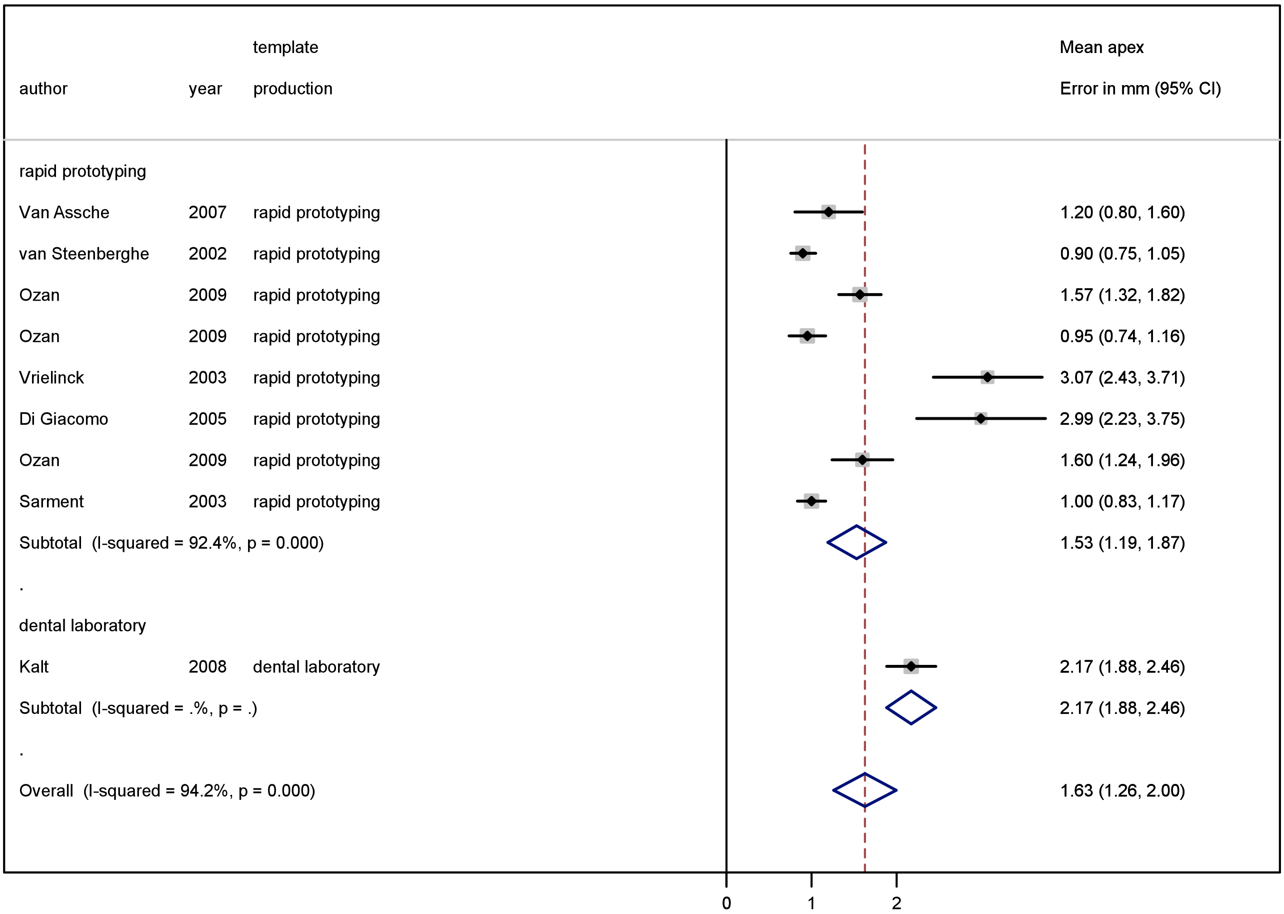

Figure 10: Deviation at apex, stratified by template production (rapid prototyping or dental laboratory)

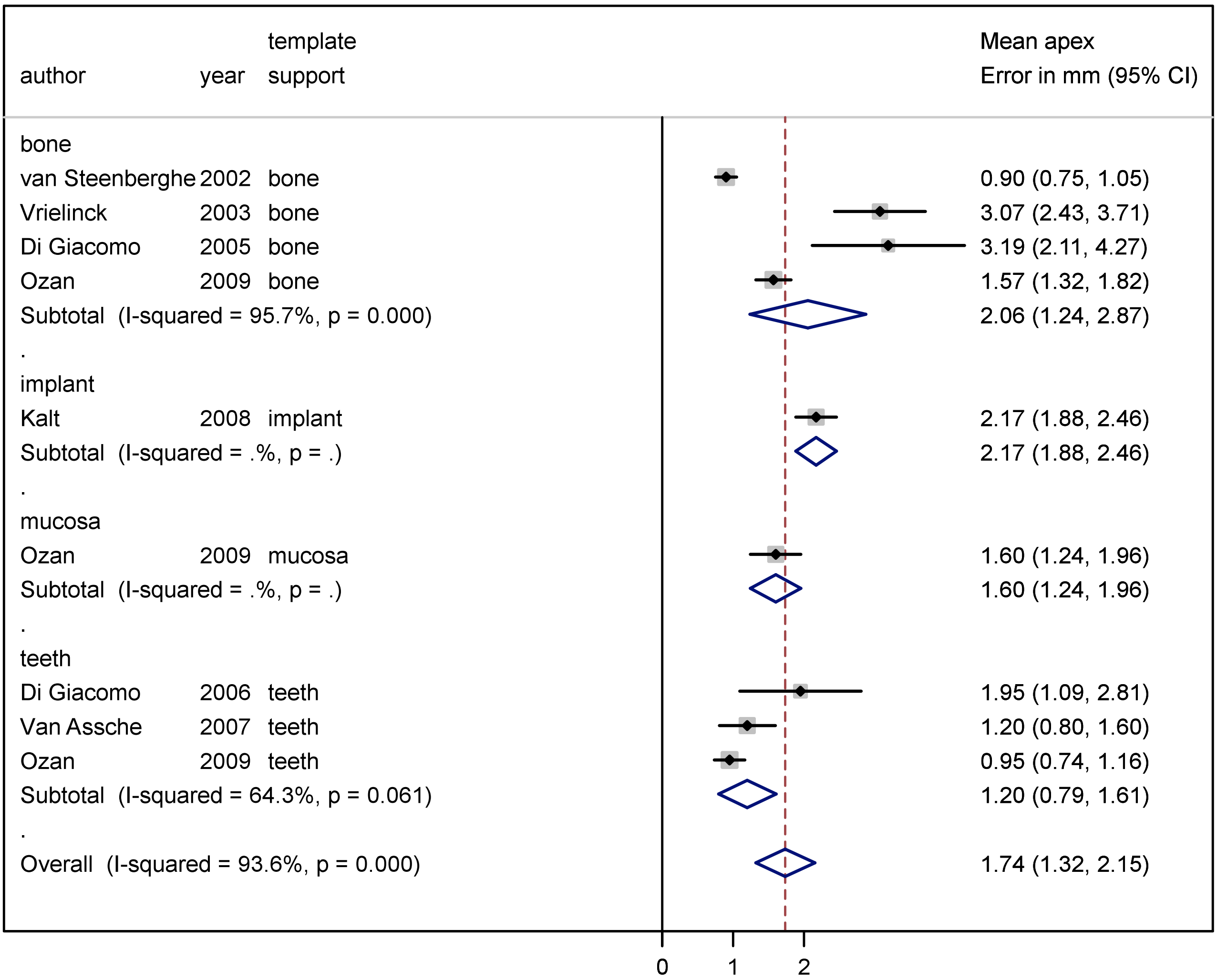

Figure 11: Deviation at entry point, stratified by template support (bone, implant, mucosa or teeth)

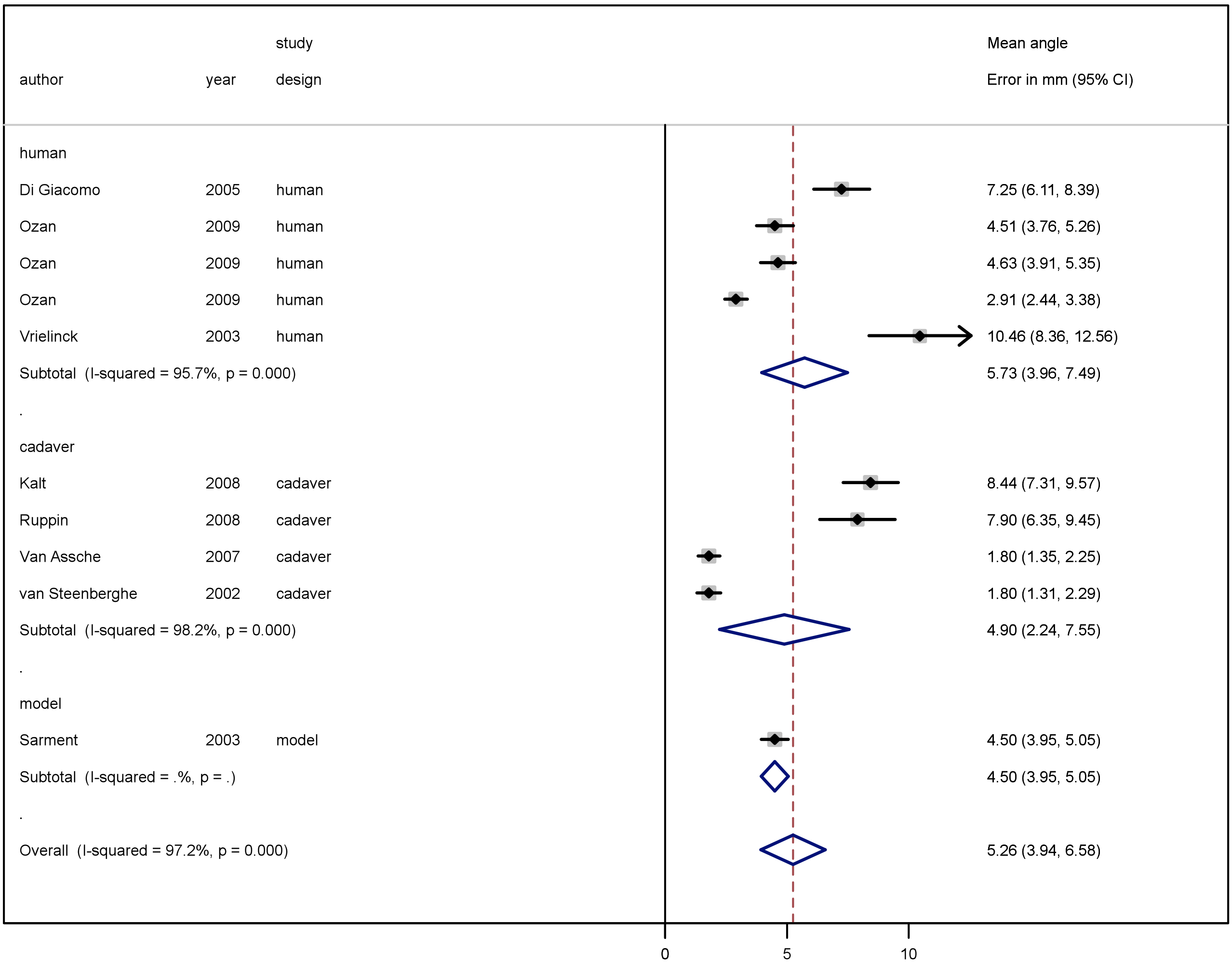

Figure 12: Deviation in angulation, stratified by study design (human, cadaver or on-vitro study)

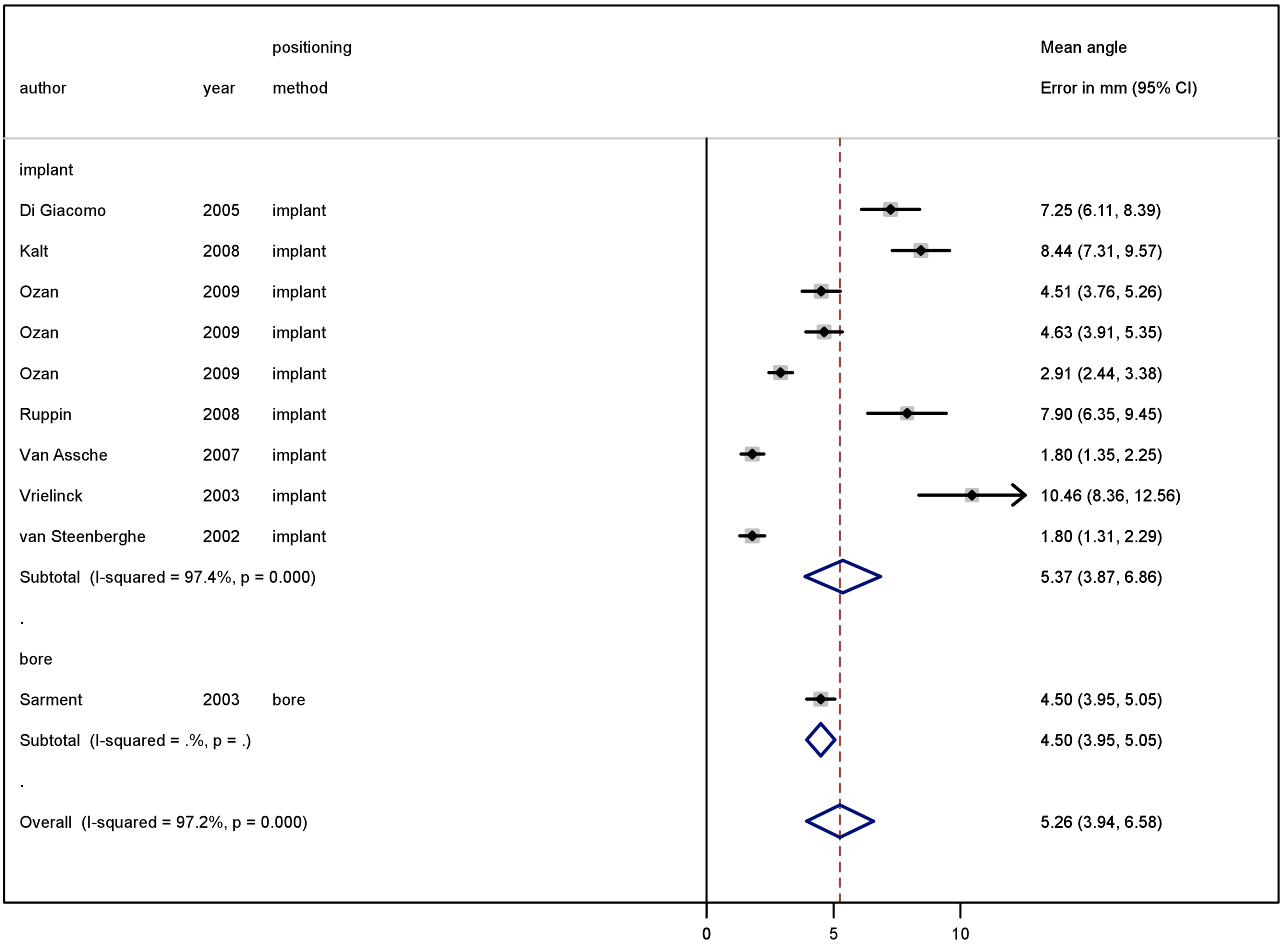

Figure 13: Deviation in angulation, stratified by positioning method (implants or bore holes)

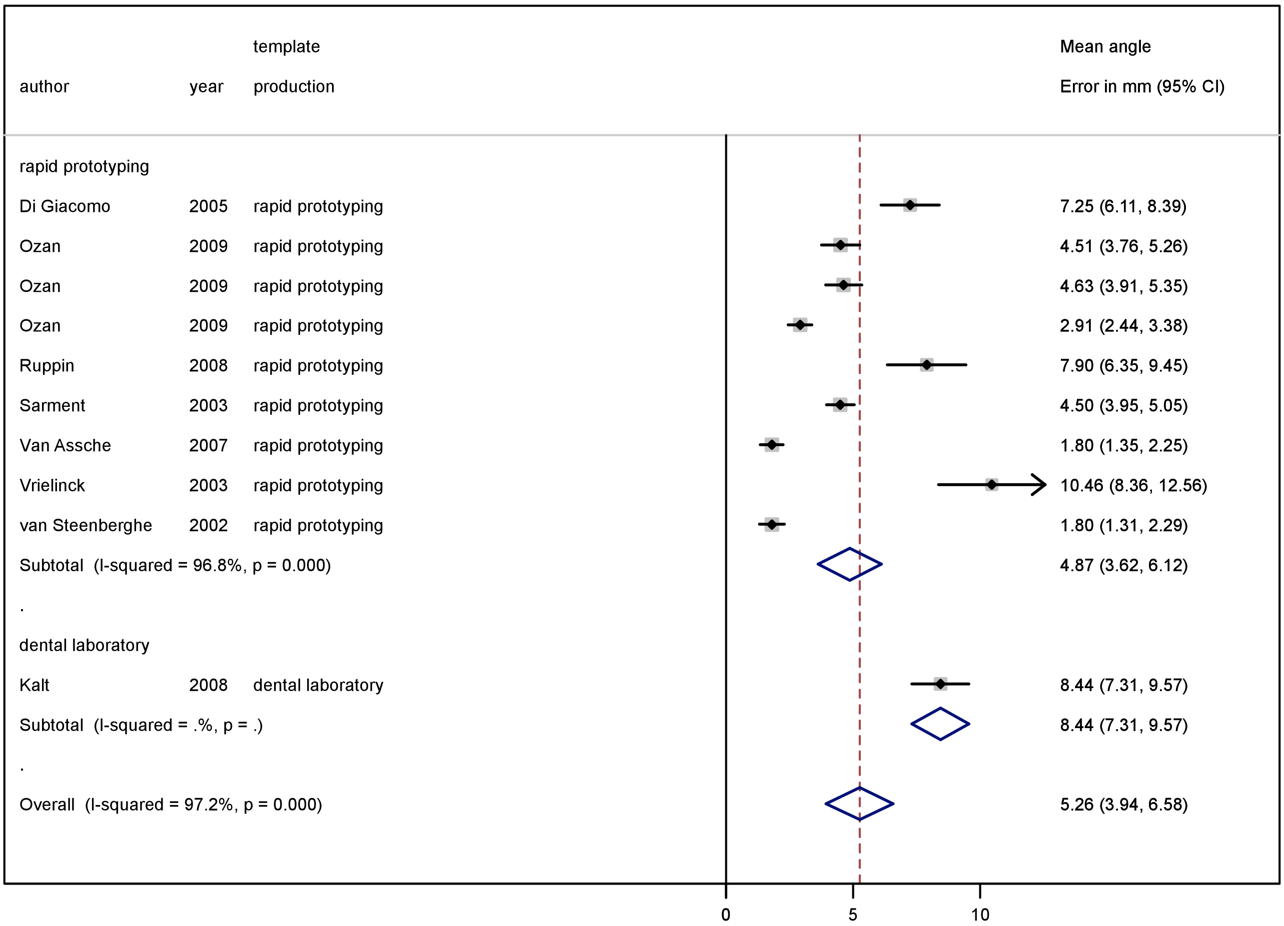

Figure 14: Deviation in angulation, stratified by template production (rapid prototyping or dental laboratory)

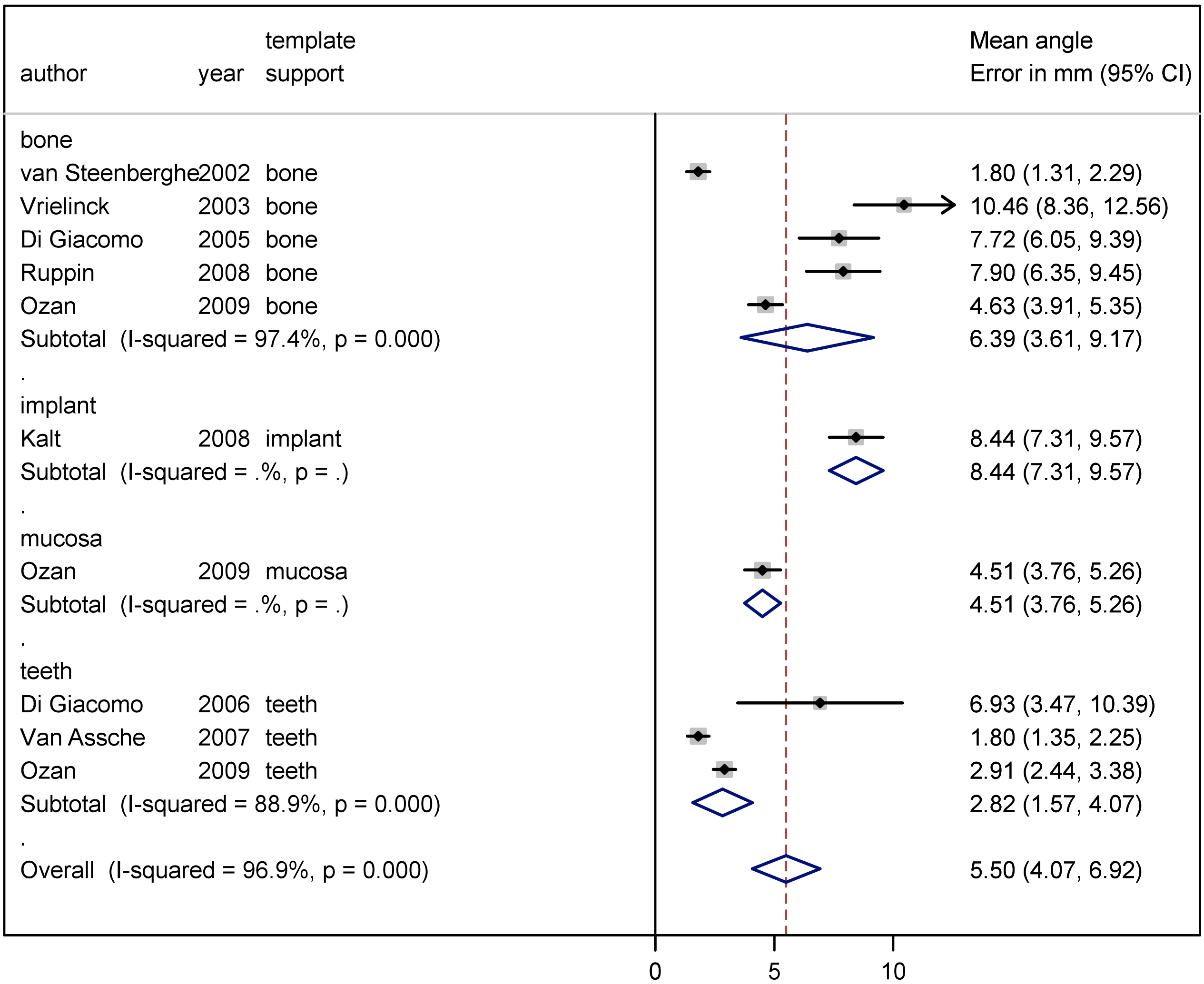

Figure 15: Deviation in angulation, stratified by template support (bone, implant, mucosa or teeth)

no.	author	year	system	template production	study design	positioning method	template support	n 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 (Di Giacomo et al. 2005)	2005	SimPlant	rapid prototyping	human	implant	bone and/or teeth	21	1.45	1.42	4.50	2.99	1.77	7.10	7.25	2.67	12.20	-	-	-
2	Sarment (Sarment et al. 2003)	2003	SimPlant	rapid prototyping	model	bore	model	50	0.90	0.50	1.20	1.00	0.60	1.60	4.50	2.00	5.40	-	-	-
3	Vrielinck (Vrielinck et al. 2003)	2003	SurgiGuide, Materialise	rapid prototyping	human	implant	bone/pins	24	1.51	-	4.70	3.07	-	6.40	10.46	-	21.00	-	-	-
4	Van Assche (Van Assche et al. 2007)	2007	Nobel	rapid prototyping	cadaver	implant	teeth or mucosa and/or pins	12	1.10	0.70	2.30	1.20	0.70	2.40	1.80	0.80	4.00	-	-	-
5	van Steenberghe (van Steenberghe et al. 2002)	2002	Nobel	rapid prototyping	cadaver	implant	bone/pins	16	0.80	0.30	-	0.90	0.30	-	1.80	1.00	-	-	-	1.10
6	Ozan (Ozan et al. 2009)	2009	Stent CAD	rapid prototyping	human	implant	bone	50	1.28	0.90	2.90	1.57	0.90	3.60	4.63	2.6	9.90	-	-	-
					human	implant	teeth	30	0.87	0.40	1.80	0.95	0.60	2.20	2.91	1.30	5.60	-	-	-
					human	implant	mucosa	30	1.06	0.60	2.60	1.60	1.00	4.10	4.51	2.10	9.00	-	-	-
7	Kalt (Kalt & Gehrke 2008)	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 (Ruppin et al. 2008)	2008	SimPlant	rapid prototyping	cadaver	implant	bone	40	1.50	0.80	3.50	-	-	-	7.90	5.00	18.50	0.60	0.40	1.40

Table 1: Accuracy studies

no	autor	year	n pat	n impl	age range	mean age	system	template fabrication	single tooth	part edent.	comp. edent.	Max.	Mand.	impl. type	flap-less	open flap	imm. rest.	delayed rest.	n surg. compl. early	reason impl. compl. early	n prosth. compl. early	reason prosthet. compl. early
1	Fortin (Fortin et al. 2003)	2003	30	101	18-70	44	CADImplant, Praxim	dental laboratory	no	yes	yes	yes	yes	n.r.	no	yes	no	yes	13	6 limited access, 1 implant unstable, 2 implant wider than planned, 1 implant shorter than planned, 3 unexpected dehiscence	n.r.	n.a.
2	Komiyama (Komiyama et al. 2008)	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 disconnections), 3 extensive adjustments of the occlusion
3	Mischkowski (Mischkowski et al. 2006)	2006	142	501	n.r.	n.r.	Med3D, Med3D GmbH	dental laboratory	yes	yes	yes	n.r.	n.r.	n.r.	n.r.	n.r.	no	yes	0	n.a.	n.r.	n.a.
			21	78	n.r.	n.r.	coDiagnostiX, IVS-Solutions	dental laboratory	yes	yes	yes	n.r.	n.r.	n.r.	n.r.	n.r.	no	yes	0	n.a.	n.r.	n.a.
			5	32	n.r.	n.r.	SimPlant, Materialise	rapid prototyping	yes	yes	yes	n.r.	n.r.	n.r.	n.r.	n.r.	no	yes	0	n.a.	n.r.	n.a.
4	Nickenig (Nickenig & Eitner 2007)	2007	102	250	22-58	40.4	coDiagnostiX, IVS-Solutions	dental laboratory	yes	yes	yes	yes	yes	n.r.	yes	yes	no	yes	13	4 limited access, 8 bone augmentation without implant placement, 1 smaller diameter than planned	n.r.	n.a.
5	Ozan (Ozan et al. 2009)	2009	30	110	37-47	47	Stent CAD, Media Lab	rapid prototyping	n.r.	yes	yes	n.r.	n.r.	Zimmer Dental	yes	yes	n.r.	n.r.	0	n.a.	n.r.	n.a.
6	van Steenberghe (van Steenberghe et al. 2005)	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	n.a.
7	Vrielinck (Vrielinck et al. 2003)	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	n.r.	n.a.
8	Yong (Yong & Moy 2008)	2008	13	78	n.r.	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

Table 2: Clinical studies reporting on early complications (n.r. = not reported; n.a. = not applicable)

early surgical complication	n 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%
prolongued pain	1	2.6%	0.2%
soft tissue defect	1	2.6%	0.2%
total	**39**	**100.0%**	**9.1%**

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

early prosthetic complication	n 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**	**100.0%**	**18.8%**

Table 4: Early prosthetic complications in 69 treated patients

no	autor	year	n pat	n impl	age range	mean age	mean follow-up (month)	follow-up range (month)	system	template fabrication	single tooth	part edent.	comp. edent.	max.	mand.	impl. type	flapless	open flap	imm. rest.	delayed rest.	n impl. compl. late	reason impl. compl. late	n prosth. compl. late	reason prosthet. compl. late
1	Fortin (Fortin et al. 2004)	2004	10	n.r.	n.r.	n.r.	12	n.r.	CADImplant, Praxim	dental laboratory	no	no	yes	n.r.	n.r.	n.r.	no	yes	yes	yes	0	n.a.	0	n.a.
2	Komiyama (Komiyama et al. 2008)	2008	29	176	42-90	71.5	n.r.	12 to 44	NobelGuide, 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 (Sanna et al. 2007)	2007	30	212	38-74	56	26.4	up to 60	NobelGuide, Nobel Biocare	rapid prototyping	no	no	yes	n.r.	n.r.	Nobel Biocare	yes	no	yes	no	9	9 implant failure	n.r.	n.a.
4	van Steenberghe (van Steenberghe et al. 2005)	2005	27	184	34-89	63	12	n.r.	NobelGuide, Nobel Biocare	rapid prototyping	no	no	yes	yes	no	Nobel Biocare	yes	no	yes	no	0	n.a.	3	1 screw loosening, 2 occlusal material fracture
5	Vrielinck (Vrielinck et al. 2003)	2003	29	71	37-71	56.4	14	n.r.	SurgiGuide, Materialise	rapid prototyping	no	no	yes	yes	no	Nobel Biocare	no	yes	no	yes	6	6 implant failure	0	n.a.
6	Yong (Yong & Moy 2008)	2008	13	78	n.r.	67.5	26.6	n.r.	NobelGuide, 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

Table 5: Late implant and prosthetic complications (n.r. = not reported; n.a. = not applicable)

late prosthetic complication	n 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%
suprastructure misfit	1	7.7%	0.9%
esthetic dissatisfaction	1	7.7%	0.9%
pressure sensivity	1	7.7%	0.9%
total	**13**	**100.0%**	**12.0%**

Table 6: Late prosthetic complications

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

Table 7: List of excluded abstracts and full text articles

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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.

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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.

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