Computer Technology Applications in Surgical Implant Dentistry: A Systematic Review

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Purpose: *To assess the literature on accuracy and clinical performance of computer technology applications in surgical implant dentistry.* ***Materials and Methods:*** *Electronic and manual literature searches were conducted to collect information about (1) the accuracy and (2) clinical performance of computer-assisted implant systems. Meta-regression analysis was performed for summarizing the accuracy studies. Failure/complication rates were analyzed using random-effects Poisson regression models to obtain summary estimates of 12-month proportions.* ***Results:*** *Twenty-nine different image guidance systems were included. From 2,827 articles, 13 clinical and 19 accuracy studies were included in this systematic review. The meta-analysis of the accuracy (19 clinical and preclinical studies) revealed a total mean error of 0.74 mm (maximum of 4.5 mm) at the entry point in the bone and 0.85 mm at the apex (maximum of 7.1 mm). For the 5 included clinical studies (total of 506 implants) using computer-assisted implant dentistry, the mean failure rate was 3.36% (0% to 8.45%) after an observation period of at least 12 months. In 4.6% of the treated cases, intraoperative complications were reported; these included limited interocclusal distances to perform guided implant placement, limited primary implant stability, or need for additional grafting procedures.* ***Conclusion:*** *Differing levels and quantity of evidence were available for computer-assisted implant placement, revealing high implant survival rates after only 12 months of observation in different indications and a reasonable level of accuracy. However, future long-term clinical data are necessary to identify clinical indications and to justify additional radiation doses, effort, and costs associated with computer-assisted implant surgery.* Int J Oral Maxillofac Implants 2009;24(suppl):92–109

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Osseointegration of dental implants is today considered to be highly predictable.[1,2] Even in patients with bone atrophy and in locations previously considered unsuitable for implants, implant placement has been made possible through bone regeneration techniques.[3,4] The predictability of these techniques has allowed placement of implants according to the prosthetic requirements.

Conventional dental panoramic tomography and periapical radiography are often performed with the patient wearing a radiographic template simulating the preoperative prosthetic design. However, these imaging techniques do not provide complete three-dimensional (3D) information of the patient's anatomy. In addition, conventional surgical templates have been fabricated on the diagnostic cast that will direct the bone entry point and angulations of the drill, but they neither reference the underlying anatomical structures nor provide exact 3D guidance.[5,6]

To overcome these limitations in dental implantology, current research has been dedicated to developing techniques that can provide optimal 3D implant positioning with respect to both prosthetic and anatomical parameters. The introduction of computed tomography (CT), 3D implant planning software, and

CAD/CAM (computer-aided design/computer-assisted manufacturing) technology have undoubtedly been important achievements in this field. The digital CT (also including cone beam CT, or CBCT) images derived in this way can be converted into a virtual 3D model of the treatment area. This provides the practitioner with a realistic view of the patient's bony anatomy, thus permitting a virtual execution of the surgery in an ideal and precise prosthetically driven manner.

Different approaches have been introduced to transfer this planned digital information to the clinical situation. Mechanical positioning devices or drilling machines convert the radiographic template to a surgical template by executing a computer transformation algorithm.[5,6] Other approaches include CAD-CAM technology to generate stereolithographic templates or bur tracking to allow for intraoperative real-time tracking of the drills according to the planned trajectory. The so-called navigation systems visualize the actual position of the surgical instrument in the surgical area on the reconstructed 3D image data of the patient on a screen "chairside" (see Appendix for definitions).

The use of these computer-assisted technologies is often restricted to the surgical aspects of implant treatment. Prosthetic treatment still has to be carried out following conventional protocols. However, the link to transfer prosthetic information to the patient is of great importance, and exact reference points are required to position the implants in such a way that prefabricated prosthetics have a precise fit.[7]

Today, a growing body of literature on the topic of computer-assisted implant dentistry is available. Authors report about different guided techniques, about the accuracy of the position of the implants compared to the virtual digital planning, and about clinical and patient-centered outcomes. As many of these techniques are already available in clinical practice or are on the way to becoming established as routine clinical treatment options, it is of great importance to analyze the currently available systems. This will allow discussion of the possibilities and limitations of computer-assisted implant dentistry in clinical applications. Hence, the aim of this systematic review was to systematically assess the literature regarding the accuracy and the clinical performance of computer technology applications in surgical implant dentistry.

MATERIALS AND METHODS

An electronic literature search of the PubMed database was performed with the intention of collecting relevant information about *(1)* the accuracy and *(2)* the clinical performance of computer-assisted implant systems. The search included articles published from 1966 up to December 2007 in the dental literature. The search was limited to studies in English, German, Italian, or French, using the terms *dental*, *implant*, *implants*, *implantation*, *implantology*, *compute**, *guid**, and *navigat**, and was performed by two independent reviewers. Every search was complemented by manual searches of the reference lists of all selected full-text articles. Additionally, full-text copies of review articles published between January 2004 and December 2007 were obtained.

Inclusion Criteria

The applied inclusion criteria were different for the studies focusing on accuracy and for the studies focusing on clinical outcomes. For the accuracy studies, clinical, preclinical, and ex vivo studies were included. The primary outcome of the experiments had to be accuracy of computer-assisted implant dentistry. Only studies providing exact information about the amount and direction of implant or instrument deviation were included.

For the clinical studies at least five patients had to be included. A follow-up period was not defined for evaluation of intraoperative complications or unexpected events during operation. However, for the evaluation of implant and prosthetic survival and complication rates, the minimum follow-up time was set at 12 months. The reported treatment outcomes had to include at least one of the following parameters: clinical, radiographic, or patient-centered outcomes of computer-assisted implant dentistry in humans.

Exclusion Criteria

Studies not meeting all inclusion criteria were excluded from the review. Case reports with fewer than five patients were not included for the analysis of accuracy or for clinical studies. Studies with zygoma implants, pterygoid implants, or mini-implants for orthodontic purposes were excluded. Publications were also excluded if the study exclusively reported on the radiographic planning.

Data Extraction

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

Statistical Analysis

The statistical analysis comprised two parts*: (1)* a summary of the evidence from the accuracy studies and *(2)* a summary of the outcomes reported from the clinical studies. For summarizing the accuracy

studies, methods appropriate for meta-analysis of the mean values observed in groups of a given size were used. The ideal information for this would be to have the mean and its standard error and then to perform inverse variance weighted fixed or random effects meta-analysis. The standard error (SE) can be derived from the observed standard deviation (SD) of the accuracy values using the formula: $SE = SD/\div\overline{n}$, where n is the number of observations in the study. Therefore, when the mean or the standard deviation was not reported in the original article, it was imputed using the available information according to the formulae given in Table 3 of the research methods article by Hozo and colleagues.[8] Heterogeneity between studies was assessed with the I^2 statistic as a measure of the proportion of total variation in estimates that is due to heterogeneity,[9] where I^2 values of 25%, 50%, and 75% are considered as cutoff points for low, moderate, and high degrees of heterogeneity. Meta-regression analyses were done to perform formal statistical tests of the differences in mean accuracy according to the groupings of the studies.[10]

For summarizing the outcomes reported from the clinical studies, methods described in detail in a systematic review of fixed partial dentures were used.[1] Briefly, for each report the event rate was calculated by dividing the number of events (failures or intraoperative complications) in the numerator by the total exposure time in the denominator. Total exposure time was approximated by multiplying the number of implants by the mean follow-up time reported in the studies. For further analysis, the total number of events was considered to conform to a Poisson distribution for a given sum of exposure time, and Poisson regression with a logarithmic link function and total exposure time per study as an offset variable were used. To assess heterogeneity of the study-specific event rates, the Spearman goodness-of-fit statistics and associated *P* value were calculated. If the goodness-of-fit *P* value was below .05, indicating heterogeneity, random-effects Poisson regression (with g-distributed random effects) was used to obtain a summary estimate of the event rates.

Summary estimates and 95% confidence intervals (95% CI) and *P* values from meta-regression or Poisson regression for assessing differences in outcomes between groups of studies are reported. All analyses were done using Stata (StataCorp) version 10.

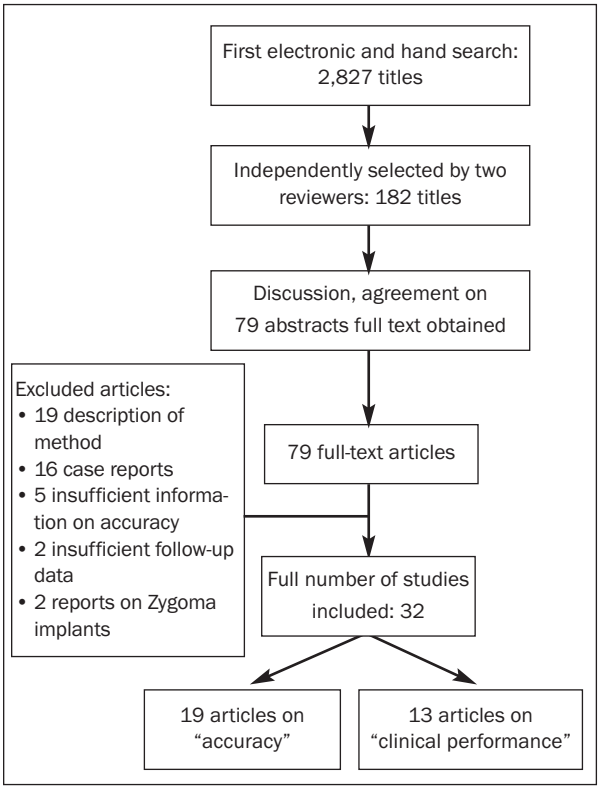

Fig 1 Literature search and selection of articles.

RESULTS

After initial identification of a total of 2,827 titles, the exclusion of irrelevant studies was performed by two independent reviewers, who reduced the number of titles to 182. After review of these manuscripts' abstracts, 85 publications were selected for full-text evaluation. Thirteen clinical and 19 accuracy studies were ultimately used for this review (Fig 1).

Table 1 Distribution and Number of Specimens (Humans, Cadavers, or Models) According to Location and Dentition

		Maxilla				Mandible							
										Edentulous			
	Specimens	Total	Edent	Part edent	Dentition unknown	Total	Edent	Part edent	Unknown	Total	Unknown	Part edent	Unknown
Model	112	46		20	26	56	29	11	16	30	1	31	10
Cadaver	6	1			1	3			3				2
Human	33					29	21		8	41	20		4
Total	151	47		20	27	88	50	11	27	71	21	31	16

Edent = edentulous; Part edent = partially edentulous.

Table 2 Extracted Data on Accuracy

	Study	Year	System	Principle	Study design	Positioning method	Sites (n)	Direction	Error entry (mm)			Error apex SD (mm)			Error angle (degrees)			Error height (mm)		
									Mean	SD	Max	Mean	SD	Max	Mean	SD	Max	Mean	SD	Max
1	Di Giacomo et al[24]	2005	SimPlant	Guide	Human	Implant	21		1.45	1.42	4.50	2.99	1.77	7.10	7.25	2.67	12.20	-	-	-
2	Sarment et al[26]	2003	SimPlant	Guide	Model	Bore	50		1.50	0.70	1.80	2.10	0.97	3.70	8.00	4.50	8.70	-	-	-
				Guide	Model	Bore	50		0.90	0.50	1.20	1.00	0.60	1.60	4.50	2.00	5.40	-	-	-
3	Van Assche et al[27]	2007	Nobel	Guide	Cadaver	Implant	12		1.10	0.70	2.30	1.20	0.70	2.40	1.80	0.80	4.00	-	-	-
4	van Steenberghe et al[28]	2002	Nobel	Guide	Cadaver	Implant	16		0.80	0.30	-	0.90	0.30	-	1.80	1.00	-	-	-	1.10
5	Kusumoto et al[11]	2006	PHANToM	Navigation	Model	Bore	6	x-axis	0.12	0.06	-	-	-	-	-	-	-	-	-	-
								y-axis	0.20	0.18	-	-	-	-	-	-	-	-	-	-
6	Chiu et al[12]	2006	IGI, DenX	Navigation	Model	Bore	80		0.43	0.56	2.23	-	-	-	4.00	3.50	13.60	0.37	0.28	1.04
7	Kramer et al[25]	2005	IGI, DenX	Navigation	Model	Implant	40		-	-	0.30	-	-	-	-	-	4.00	-	-	0.30
8	Brief et al[29]	2001	IGI, DenX	Navigation	Model	Bore	38	x-axis	0.50	-	1.10	0.60	-	1.10	-	-	-	0.20	-	0.70
								y-axis	0.30	-	0.90	0.30	-	1.00	-	-	-	0.20	-	0.70
				Navigation	Model	Bore	8	x-axis	0.30	-	0.60	0.20	-	0.30	-	-	-	0.20	-	0.50
								y-axis	0.20	-	0.50	0.60	-	1.20	-	-	-	0.20	-	0.50
9	Widmann et al[5]	2005	Treon	Navigation	Model	Bore	112		0.42	0.26	1.00	-	-	-	-	-	-	0.25	0.12	0.60
10	Widmann et al[30]	2007	Treon	Guide	Model	Bore	56		-	-	-	0.50	0.30	1.20	-	-	-	-	-	-
				Guide	Model	Bore	56		-	-	-	0.60	0.30	1.40	-	-	-	-	-	-
				Navigation	Model	Bore	56		-	-	-	0.40	0.30	1.00	-	-	-	-	-	-
11	Wittwer et al[31]	2006	Treon	Navigation	Human	Implant	80		1.20	0.80	3.40	0.80	0.60	2.00	-	-	-	-	-	-
12	Gaggl et al[14]	2002	SNM	Navigation	Model	Bore	60		0.20	-	-	-	-	-	-	-	-	0.11	0.22	0.60
				Navigation	Model	Implant	60		0.20	-	-	-	-	-	-	-	-	0.25	0.26	0.90
13	Gaggl et al[13]	2001	SNM	Navigation	Model	Bore	100		-	-	-	-	-	-	-	-	-	0.14	0.05	0.23
14	Wanschitz et al[32]	2002	VISIT	Navigation	Cadaver	Implant	20	Buccal	0.55	0.31	1.50	1.44	0.79	3.50	-	-	-	-	-	-
								Lingual	0.49	0.38	1.40	1.36	0.70	3.20	-	-	-	-	-	-
15	Wanschitz et al[33]	2002	VISIT	Navigation	Cadaver	Implant	15	Buccal	0.58	0.40	1.40	0.79	0.71	3.10	3.55	2.07	10.40	-	-	-
								Lingual	0.57	0.49	1.80	0.77	0.63	2.90	-	-	-	-	-	-
16	Wagner et al[34]	2003	VISIT	Navigation	Human	Implant	32	Lingual	1.00	0.50	2.60	1.30	0.90	3.50	6.40	-	17.40	-	-	-
								Buccal	0.80	0.30	2.10	1.10	0.90	3.40	-	-	-	-	-	-
17	Hoffmann et al[15]	2005	Vector Vision	Navigation	Model	Bore	240		0.95	0.25	-	-	-	-	1.35	0.42	-	0.97	0.34	-
18	Brief et al[16]	2005	Robodent	Navigation	Model	Bore	15		0.35	0.17	0.75	0.47	0.18	0.72	2.12	0.78	3.64	0.32	0.21	0.71
			IGI, DenX	Navigation	Model	Bore	15		0.65	0.58	2.37	0.68	0.31	1.22	4.21	4.76	20.43	0.61	0.36	1.43
19	Wittwer et al[17]	2007	VISIT	Navigation	Human	Implant	32	Buccal	1.00	0.50	2.00	0.60	0.20	0.90	-	-	-	-	-	-
								Lingual	0.70	0.30	1.20	0.70	0.30	1.00	-	-	-	-	-	-
			Treon	Navigation	Human	Implant	32	Buccal	1.00	0.50	2.40	0.80	0.60	2.00	-	-	-	-	-	-
								Lingual	1.20	0.80	3.40	0.70	0.50	1.60	-	-	-	-	-	-

Table 3 Systems Used in Studies Reporting on Accuracy

System	No. of studies
Dynamic	
IGI, DenX	5
VISIT	4
Treon	4
SMN, Zeiss	2
Vector Vision	1
Robodent	1
PHANToM	1
Static	
SimPlant	2
Nobel Biocare	2

Table 4 Distribution and Number of Evaluated Sites in Terms of Accuracy

	No. of sites	No. of studies
Navigation	1,041	14
Guide	261	5
Model	1,042	10
Cadaver	63	4
Human	197	5
Drill	942	10
Implant	360	9

Accuracy Studies

Literature. Nineteen articles from the systematic review, published from 2001 to 2007, provided useful information about accuracy in computer-assisted implant dentistry. Twelve research groups from seven countries were involved.

Material. Eleven in vitro studies were performed on models, mostly made of acrylate. Of the remaining eight studies, four reported the use of human cadavers and four were available as clinical studies with a total of 45 patients. In 16 of these patients, implants were placed in an edentulous mandible, in 20 cases in edentulous jaws without further specification, and in the remaining cases the location was not reported (Tables 1 and 2).

Systems. Nine different computer-assisted implantation systems were tested (Table 3). The majority of the systems were "dynamic" systems, based on intraoperative feedback produced by recording the position of the handpiece with infrared cameras (six systems) or by haptic feedback (one system, PHANToM[11]). These navigational systems were used in 19 studies at 1,041 implant sites (Tables 2 and 4). Two of the nine systems used drill guides, based on the computer-assisted implant planning; 261 implant sites were drilled or implanted with the assistance of a drill guide.

Drillings/Implants/Positions and Their Evaluation. A total of 1,302 positions were evaluated (Tables 2 and 4); 360 of the positions were measured on implants, with 100 of these placed in models, 63 in human cadavers, and 197 in humans. The remaining 942 positions were assessed on drill holes made in models. In the majority of the studies (14 studies) a CT scan was performed to assess the accuracy, whereas only in three studies was the position of the drill holes or implants directly measured in models.[12–14] Calculation of the error by registration of the handpiece or 3D probe position after drilling and by coordinate measurements was used in two studies.[15,16]

To assess the accuracy of the implant systems, the following parameters were selected:

a. Deviation error in a horizontal direction at the entry point of the drill or implant
b. Beviation error in a horizontal direction at the apex of the drill or implant
c. Deviation in height (vertical direction)
d. Deviation of the axis of the drill or implant

For the first two parameters, the extracted data allowed a statistical analysis (Table 2). Regarding the latter two parameters, data were insufficient for a meta-analysis.

(a and b) Error at Entry Point and Apex (Figs 2 to 9). The overall mean error at the entry point was 0.74 (95% CI: 0.58 to 0.90) mm with a maximum of 4.5 mm, while the mean error at the apex was 0.85 (95% CI: 0.72 to 0.99) mm with a maximum of 7.1 mm.

With systems using surgical guides, the mean error was 1.12 (95% CI: 0.82 to 1.42) mm (max 4.5 mm) at the entry point and 1.2 (95% CI: 0.87 to 1.52) mm (max 7.1 mm) at the apex. For dynamic intraoperative navigation (14 studies) the mean error was 0.62 (95% CI: 0.43 to 0.81) mm (max 3.4 mm) at the entry point and 0.68 (95% CI: 0.55 to 0.80) mm (max 3.5 mm) at the apex. The dynamic systems showed a statistically significantly higher mean precision by 0.5 mm ($P = .0058$) at the entry point and by 0.52 mm ($P = .0354$) at the apex.

Implants positioned in humans showed a higher mean deviation at entry point and apex compared to implants or drills in cadaver studies (Δ entry = 0.32 mm, $P = .0497$; Δ apex = 0.02 mm, $P = .8546$) and studies on models (Δ entry = 0.43 mm, $P = .0015$; Δ apex = 0.33 mm, $P = .1245$).

The mean error was significantly higher in studies in which the position of implants was measured, compared to studies in which the position of drill holes was assessed (Δ entry = 0.3 mm, $P = .0103$; Δ apex = 0.33 mm, $P = .0578$).

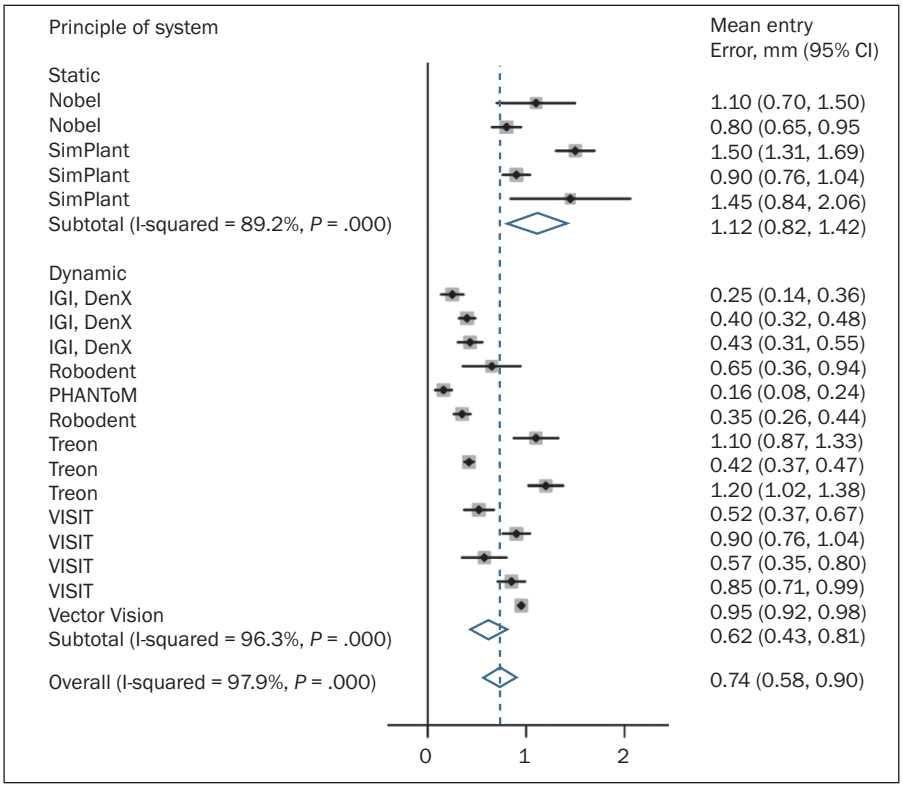

Fig 2 Mean deviation at entry point, stratified by principle of system (static vs dynamic).

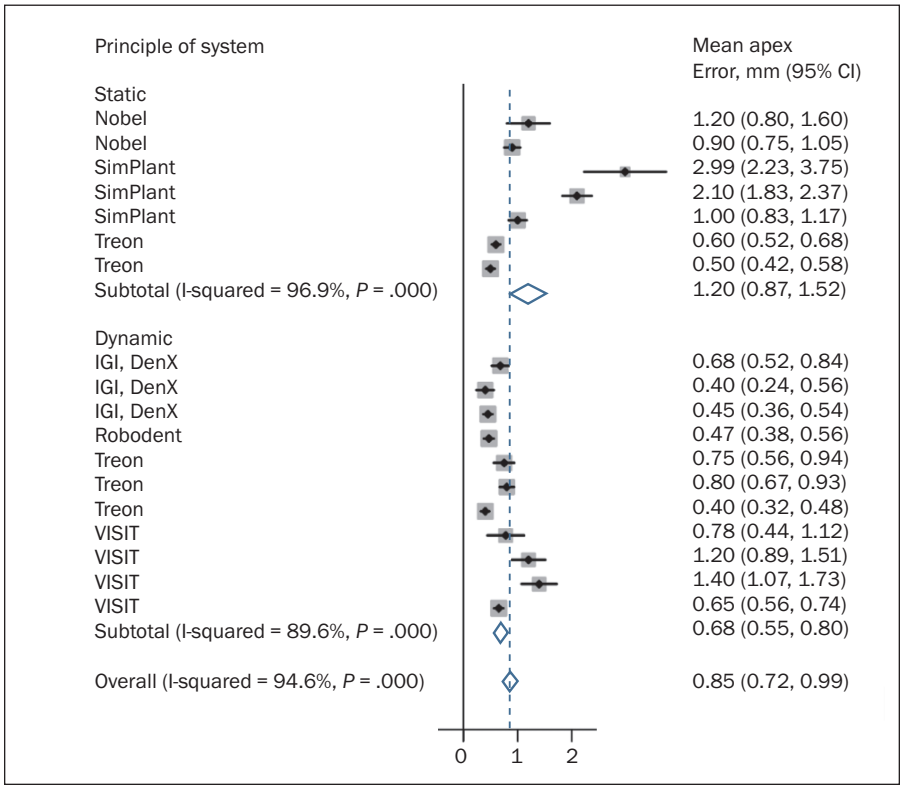

Fig 3 Mean deviation at apex, stratified by principle of system (static vs dynamic).

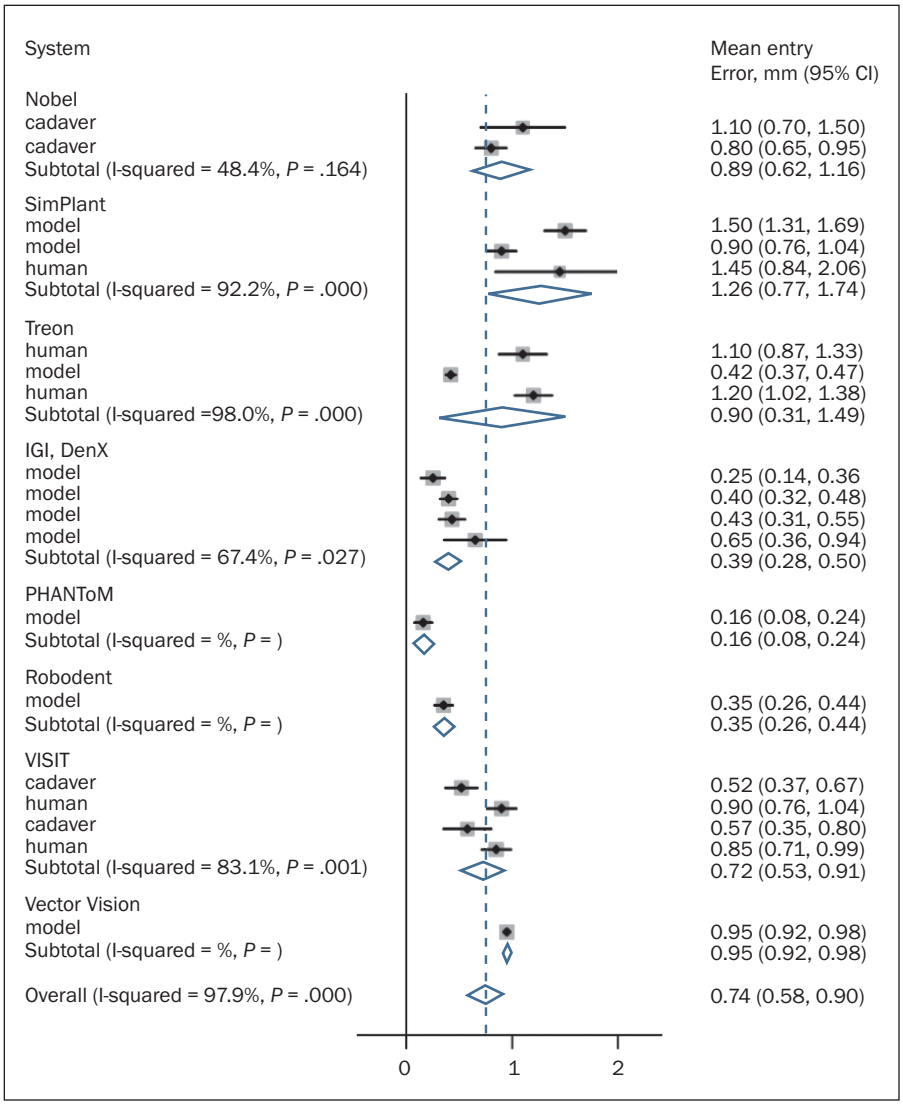

Fig 4 Mean deviation at entry point, stratified by system.

(c) Error in Height (Table 2). The mean error in height was reported in seven studies, all of which were performed on models using a dynamic implant system. Only one of these seven studies used implants[14]; all others used drill holes for the evaluation of the system accuracy. The median error in height was 0.23 mm, with a maximum of 1.43 mm.

(d) Error in Angulation (Table 2). Information about the deviation in angulations was found in nine studies. The median error in angulation was 4.0 degrees, with a maximum of 20.43 degrees.

Clinical Studies

Literature. Thirteen human studies identified by systematic review and published from 2001 to 2007 provided information about clinical, radiographic, or patient-centered outcomes in computer-assisted implant dentistry. Only two studies were randomized controlled clinical studies,[17,18] whereas the remaining 11 studies were prospective studies.

Material. A total of 580 patients with 1,243 implants were treated with computer-assisted implant dentistry and have been included in this review. The mean age was 56.1 years, with a range from 18 to 89 years. The mean follow-up period was 7.7 (0 to 26.4) months. The majority of the studies reported on edentulous patients in the maxilla and mandible. However, there were also studies treating single-tooth gaps and partially edentulous patients.

In 6 of the 13 included studies an immediate restoration of the implants was performed. In addition, all of these implants were inserted using a flapless procedure (Table 5).

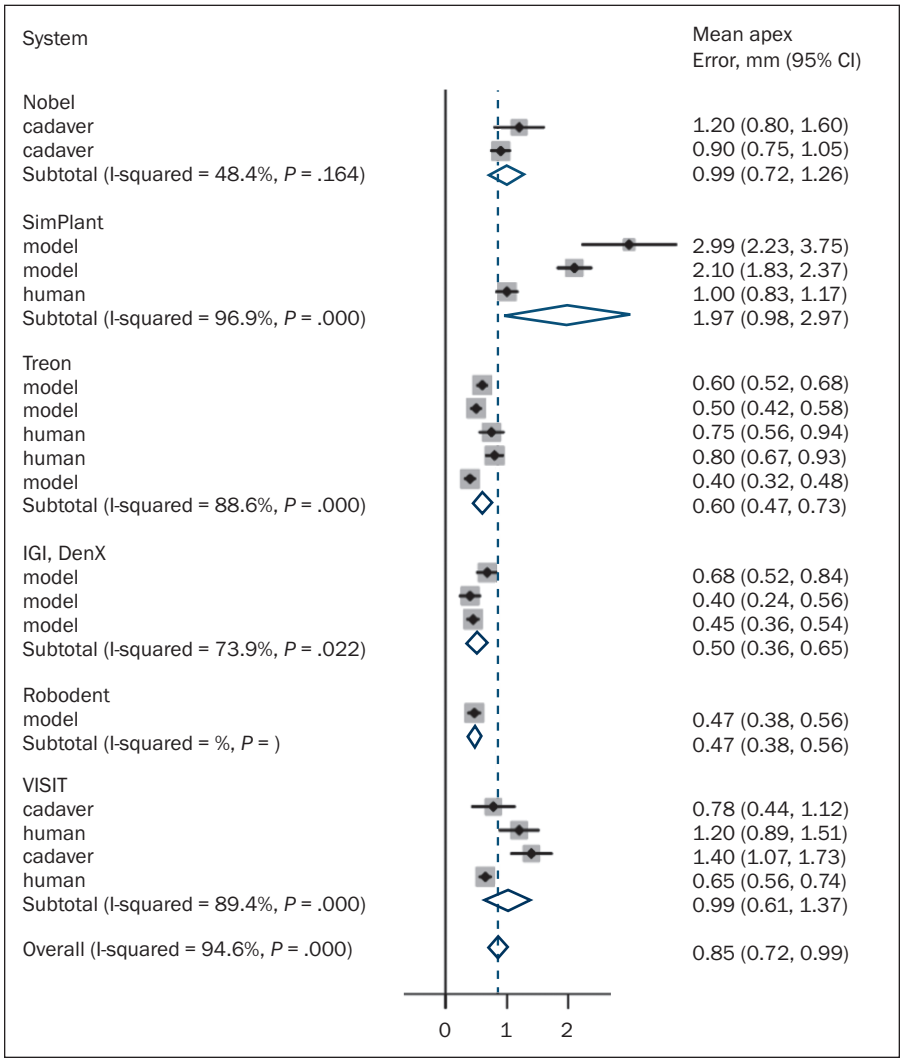

Fig 5 Mean deviation at apex, stratified by system.

Systems. The included studies reported about 10 different dynamic and static systems (Table 6). In all except one study,[19] in which a cone beam technique was used for preoperative planning, a CT scan was performed for that purpose.

Treatment Outcomes. The majority of the studies described intraoperative complications and reliability of the implant placement after computer-assisted implant planning. Other studies have looked at the assessment of pain, the operating room time, and marginal bone remodeling. Due to the short mean observation time, it was difficult to assess implant survival or success rates. However, 5 of the 13 studies reported an observation period of at least 12 months (Table 7). These studies have been included in the statistical analysis.

The mean annual implant failure rate for all 5 studies was 3.36%, ranging from 0% to 8.45%. In immediately restored cases the failure rate was significantly lower ($P = .0018$) by a factor of 5. A delayed restoration protocol was used in only one study with 29 patients and 71 implants.[20]

Ten of 13 studies reported on intraoperative complications, including interocclusal distances that were too limited to perform guided implant placement, limited primary stability of the inserted implants, or the need for additional grafting procedures (see Table 5). Intraoperative complications or unexpected events were observed in 4.6% (95% CI: 1.2% to 16.5%) of the implant placements. Dynamic systems showed a 2.2 times higher incidence of complications, although this ratio was not significant ($P = .5282$). In flapless procedures, the rate ratio for complications was 0.15 (95% CI: 0.03 to 0.88, $P = .035$), 7 times lower compared to procedures with an open flap. In edentulous patients, the rate ratio for complications was 0.23 (95% CI: 0.02 to 2.6, $P = .237$), 4 to 5 times lower than in partially edentulous patients.

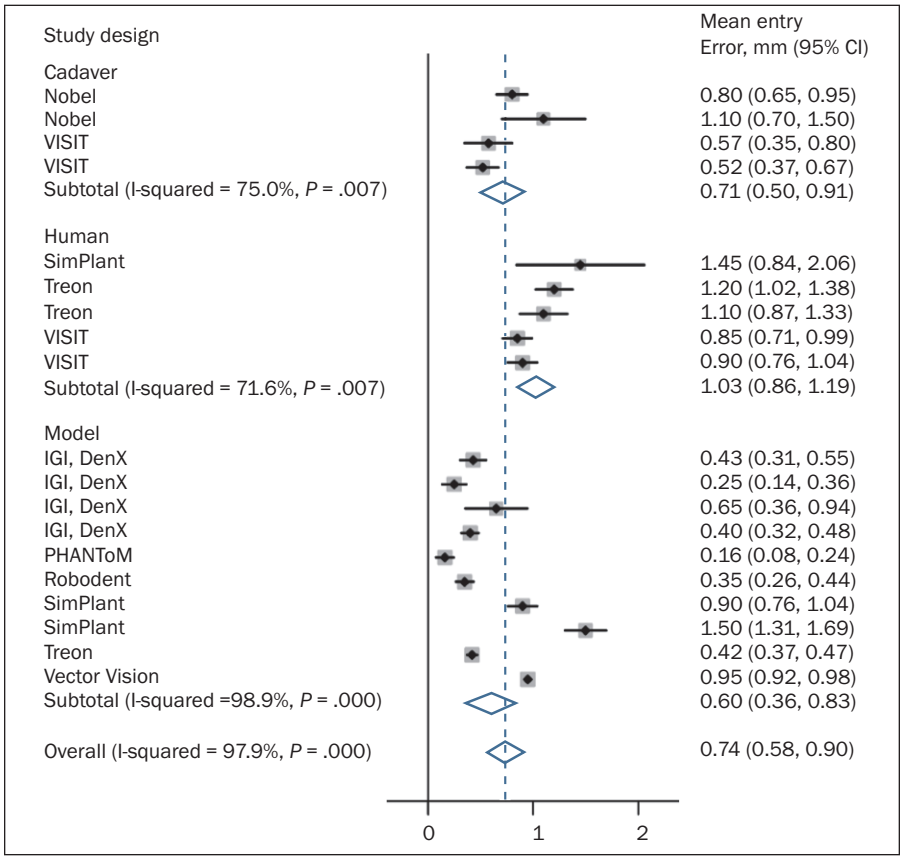

Fig 6 Mean deviation at entry point, stratified by study design (cadaver, human, model).

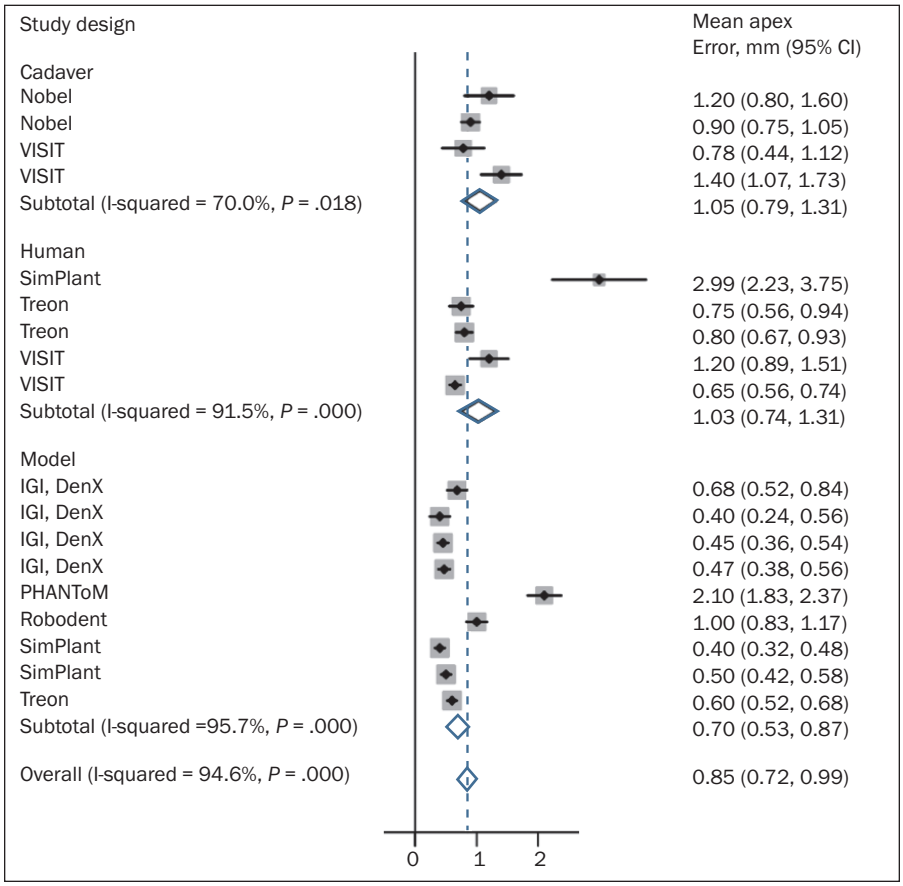

Fig 7 Mean deviation at apex, stratified by study design (human, cadaver, model).

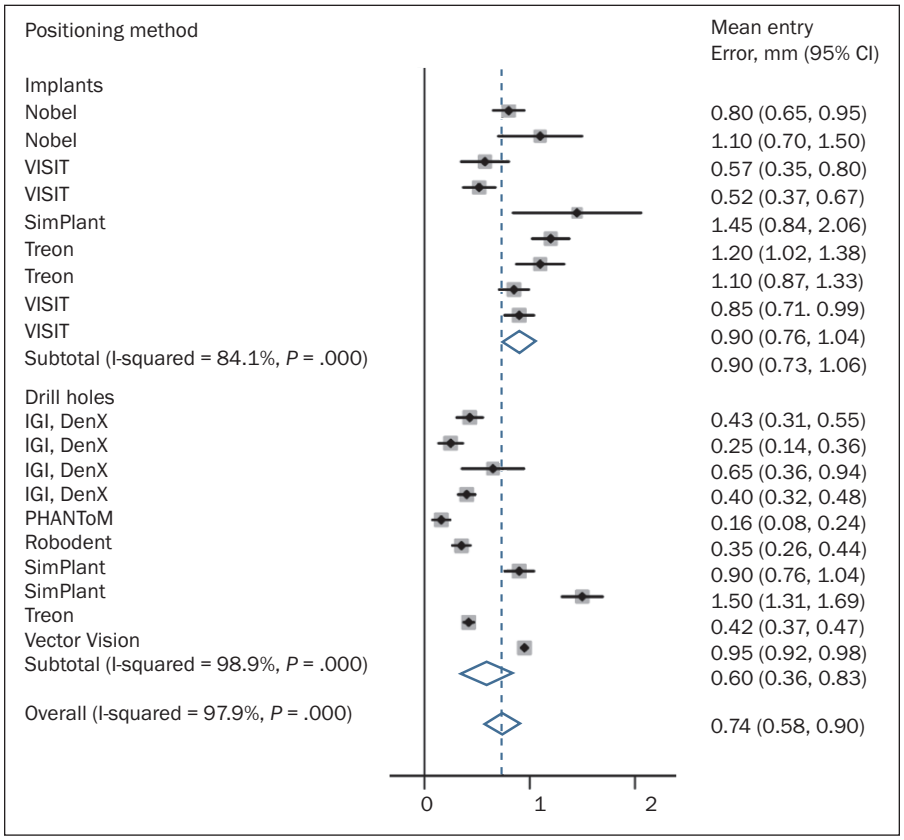

Fig 8 Mean deviation at entry point, stratified by positioning method (implants vs drill holes).

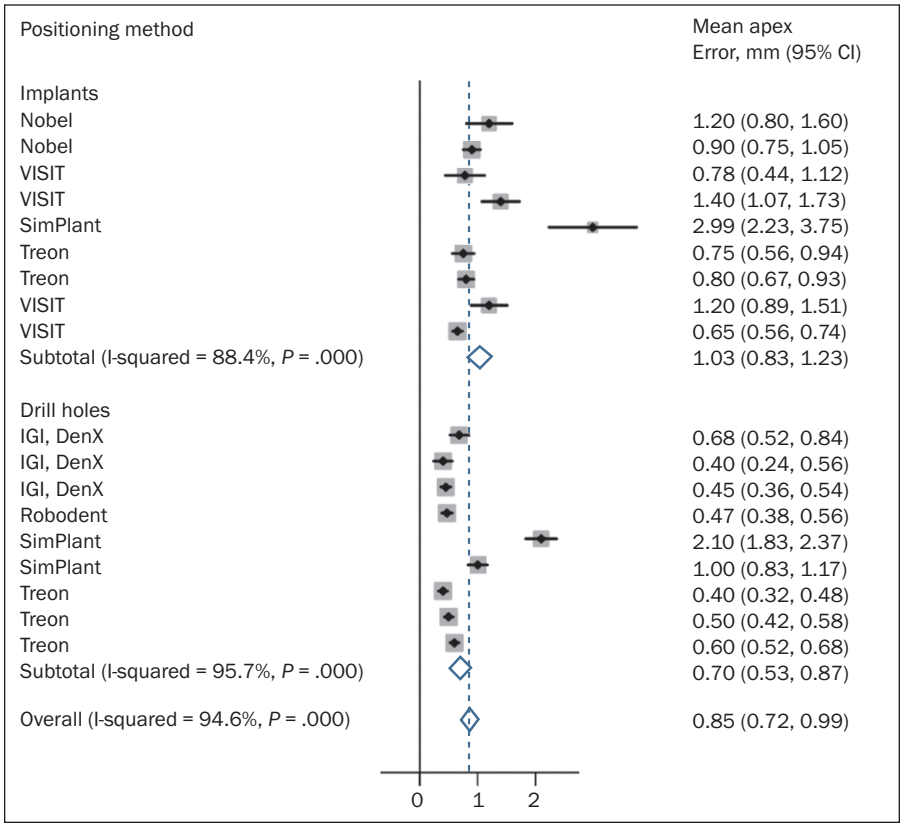

Fig 9 Mean deviation at apex, stratified by positioning method (implants vs drill holes).

Table 5 Clinical Studies

Study		Year	Study design	No. of patients	No. of implants after dropout	Age range (y)	Mean age (y)	Follow-up period (mo)	System	Dynamic intraop nav	Single tooth	Part edent	Comp edent	Max	Mand	Implant type	Flapless	Imm rest	No. of implant complications intraop	No. of implant failures	No. of prosthetic failures
1	Siessegger et al[35]	2001	Prospective	5	18	NR	NR	0	Vector Vision 2	1	0	1	1	1	0	Frialit 2	0	0	7	NR	NR
2	Mischkowski et al[22]	2006	Prospective	142	501	NR	NR	6	Med3D	0	1	1	1			NR	NR	0	0	8 (1.31%)	NR
			Prospective	21	78	NR	NR	6	coDiagnostiX	0	1	1	1			NR	NR	0	0		NR
			Prospective	5	32	NR	NR	6	SimPlant	0	1	1	1			NR	NR	0	0		NR
			Prospective	20	71	NR	NR	6	Robodent	1	1	1	1			NR	NR	0	0	4 (2.96%)	NR
			Prospective	18	64	NR	NR	6	Vector Vision 2	1	1	1	1			NR	NR	0	0		NR
3	Wittwer et al[31]	2006	Prospective	20	78	53–75	61.4	4	Stealth Station Treon	1	0	0	1	0	1	Ankylos	1	0	2	2	NR
4	Wittwer et al [36]	2007	Prospective	25	88	55–77	62.1	24	Stealth Station Treon	1	0	0	1	0	1	Ankylos	1	1	4	2	0
5	Wittwer et al [17]	2007	RCT	16	64	56–77	63.4	0	Stealth Station Treon/VISIT	1	0	0	1	0	1	Ankylos	1	1	0		
6	Wittwer et al [37]	2007	Prospective	20	80	56–77	64.3	0	VISIT	1	0	0	1	0	1	Ankylos	1	1	2	0	NR
7	Fortin et al[18]	2006	RCT	60	152	19–82	50	0.25	CADImplant	0	0	1	1			NR	1	NR	NR	NR	NR
8	van Steenberghe et al[38]	2005	Prospective	27	164	34–89	63	12	NobelGuide	0	0	0	1	1	0	Nobel Biocare	1	1	0	0	0
9	Fortin et al[39]	2004	Prospective	10	NR	NR	NR	12	CADImplant	0	0	0	1			NR	1	1	NR	0	0
10	Fortin et al[40]	2003	Prospective	30	95	18–70	44	0	CADImplant	0	0	1	1			NR	0	0	14	NR	NR
11	Nickenig and Eitner[19]	2007	Prospective	102	250	22–58	40.4	0	coDiagnostiX	0	1	1	1			NR	1	0	13	0	NR
12	Sanna et al [21]	2007	Prospective	30	183	38–74	56	26.4	NobelGuide	0	0	0	1			Nobel Biocare	1	1	NR	9 (4.9%)	NR
13	Vrielinck et al[20]	2003	Prospective	29	71	37–71	56.4	14	SurgiGuide, Materialise	0	0	0	1	1	0	Nobel Biocare	0	0	0	6	0
	Total			580	1,243		56.1	7.7		5	6	9	17	3			4	0	9	6	42

nav = navigation; Part edent = partially edentulous; Comp edent = completely edentulous; Max = maxilla; Mand = mandible; Imm rest = immediate restoration; NR = not reported.

Table 6 Systems Used in Studies Reporting on Clinical Outcome

System	No. of studies	No. of patients	No. of implants
Dynamic			
VISIT	2	28	122
Treon	3	53	198
Vector Vision	2	23	82
Robodent	1	20	71
Static			
SimPlant	1	5	32
SurgiGuide	1	29	71
Nobel Guide	2	57	347
coDiagnostiX	2	123	325
CADImplant	3	100	247
Med3D	1	142	501

Table 7 Implant Failures, Follow-up Period and Annual Failure Rates

Study	Year	Principle	No. of patients	No. of implants after dropout	No. of failures	% failures	Follow-up period (mo)	Failure rate (events per 100 y)
Wittwer et al[36]	2007	Navigation	25	88	2	2.27%	24	1.1
van Steenberghe et al[38]	2005	Guide	27	164	0	0.00%	12	0
Fortin et al[39]	2004	Guide	10	NR	0	0.00%	12	0
Sanna et al[21]	2007	Guide	30	183	9	4.92%	26.4	2.2
Vrielinck et al[20]	2003	Guide	29	71	6	8.45%	14	7.2
Total			121	506	17	3.36%		
Summary rate (95% CI)								2.4 (0.8–7.6)

NR = not reported.

One randomized clinical trial compared pain experience after implant placement with either an open-flap or a flapless surgical procedure.[18] The results showed a significant difference in pain measurements, with higher scores on the visual analog scale with the open-flap surgery.

Very limited data are available regarding prosthetic complication rates.

DISCUSSION

This review systematically assessed the literature regarding accuracy and clinical performance of computer-assisted implant dentistry. In the dental literature, 28 different image guidance systems are described (Appendix, Table 8). Based on five included clinical studies with a total of 506 implants using computer-assisted implant dentistry, it was demonstrated that the mean annual failure rate was 3.36% (0% to 8.45%) after an observation period of at least 12 months. As assessed by 19 clinical and preclinical studies, the accuracy at the entry point revealed a mean error of 0.74 mm, with a maximum of 4.5 mm, while at the apex the mean error was 0.85 mm, with a maximum of 7.1 mm.

Clinical Outcomes

It is important to distinguish between clinical studies reporting about dynamic navigation systems and about static template-based guidance systems. The majority of clinical studies have investigated the template-based guidance systems. The overall mean survival rate of 96.6% after 1 year is considered to be rather high. However, it is difficult to compare with other systematic reviews reporting implant survival rates ranging from 95.4% (implant-supported fixed partial dentures) to 96.8% (single-tooth implants) after 5 years, due to the lack of long-term data for the guided implant placements.[1,2] Only one study is available with an observation period of more than 2 years, and this reveals an implant survival rate of 95.1% using a template-based guidance system and a prefabricated fixed prosthesis that was immediately loaded.[21] To evaluate a new operation technique, it is important to know not just the implant survival rate but also the practicality of the method in clinical practice. In 4.6% of the cases, intraoperative complications or unexpected events were reported, including *(1)* interocclusal distances that were too limited to perform guided implant placement, *(2)* limited primary stability of the inserted implants, or *(3)* the need for additional grafting procedures. Since they are not

always reported and there is no consistent definition of a complication or an unexpected event, the data must be interpreted with caution. In addition, the rate for intraoperative complications and unexpected events was six times lower in flapless procedures. It might be possible that due to the lack of visual access, the complication rate in terms of implant malpositioning and the need for additional grafting procedures might be underestimated. However, this finding is only based on very limited data and should be further evaluated in future study designs.

It is clearly beyond the intent or scope of this review to judge the benefits or merits of navigation versus template-based guidance systems. Only one included study performed a comparison of the two.[22] It was reported that the static approach has a clear advantage due to the uncomplicated intraoperative handling of the surgical templates and the less expensive equipment. Additionally, the process can be planned by the surgeon and/or coworkers, or in cooperation with the company which is responsible for the fabrication of the templates. In contrast, with the dynamic system the time spent on presurgical set-up and intraoperative application can be considered significantly longer, partly due to the navigation device. High purchase and maintenance costs of the systems have to be taken into consideration.[22] In general, today there seems to be a trend toward the static template-based guidance systems in dental implantology.

A consensus workshop organized by the European Association of Osseointegration raised several questions, including which clinical indication would potentially benefit from computer-assisted implant dentistry.[23] The present systematic review included studies reporting about edentulous, partially edentulous, and single-tooth replacement cases. The majority of the included studies reported about edentulous cases. The reason may be the better cost-benefit ratio and the better acceptance of additional radiographic examinations (CT scans) in patients with completely edentulous ridges compared to single-tooth replacements. However, in the future, reductions in radiation doses through improved radiographic techniques (ie, cone beam technique) and greater accuracy might increase the number of indications for computer-assisted implant placement.

Accuracy

Computer-assisted implant dentistry has often been recommended for flapless procedures and for implant placements in situations with a limited amount of bone or proximity to critical anatomical structures. Hence, it is of utmost importance to know the accuracy of the dynamic and static systems available for implant dentistry. In this systematic review, the accuracy in computer-assisted implant dentistry was assessed by including various methods of evaluation (mostly CT, but also direct measurements of sectioned models or registration of the handpiece position), and by including preclinical and clinical models. In general, the accuracy was better in studies with models and cadavers than in studies with humans. This can be explained by better access, better visual control of the axis of the osteotomy, no movement of the patient, and no saliva or blood in the preclinical models. There was no significant difference between cadavers and models; therefore, the influence of the material (bone versus acrylic) might be negligible for testing the accuracy in a preclinical model. However, it is recommended that the accuracy be assessed in clinical situations. This recommendation is supported by the results of this review, in which the highest number of deviations were revealed in human studies compared to preclinical models (see Table 7). In addition, it is more important to report the maximum deviation, which is crucial to prevent damage of anatomical structures, than to report the mean deviation.

One included study using a static template-based system reported a maximum deviation of 4.5 mm at the entry point.[24] This is by far the highest value for deviation reported in all studies in the present review. The authors proposed that this difference might result from movements of the surgical guide during implant preparation. They suggested further improvements to provide better stability of the template during surgery when unilateral bone-supported and non–tooth-supported templates are used.[24]

In the present systematic review, the overall mean error at the entry point was 0.74 mm. To interpret this value it is important to know the accuracy of manual implant preparation. Two preclinical studies performed on acrylic models compared the accuracy of two dynamic navigated systems with conventional implant preparation.[16,25] In one study, the reported maximum error at the entry point ranged from 0.8 to 1 mm for the conventional insertion and was 0.6 mm for the navigated insertion.[25] The other study reported a mean error at the entry point of 1.35 mm for manual implantation and 0.35 to 0.65 mm (RoboDent and IGI DenX Systems) for dynamic navigated implant placement. These values are in accordance with the mean error at the entry point in preclinical models revealing a difference of 0.6 mm in the present review. Both studies demonstrated a statistically significantly higher accuracy for the navigated systems compared to the manual implant placement.[16,25] However, this comparison was only performed on dynamic navigated systems, and no data for static template-based systems are available. This is even more important because the

dynamic systems in the present systematic review provided greater accuracy than the static systems. This difference might be explained by the fact that static template-based systems were more often used clinically rather than in preclinical models, which have provided better accuracy.

Because of different study designs (human versus cadaver or model, drill holes versus implants, different evaluation methods), it is not possible to identify one system as superior or inferior to others.

A series of errors during the entire diagnostic and operative procedure might contribute to an accumulation of minor errors, leading to larger deviations of the implant position. The reproducibility of the template position during radiographic data acquisition and during implantation is a delicate issue, especially in edentulous patients.

In addition, it is important to realize that computer-assisted implant surgery is a new field of research that is undergoing rapid development and improvements in clinical handling properties and accuracy. Hence, the systems used today in clinical practice might demonstrate greater accuracy and might have solved some of the above-mentioned problems encountered with earlier versions, but these data are not yet available in the dental literature. This rapid advancement in computer technology should be considered when evaluating older reports of various systems, since those that were tested may not bear much similarity to current offerings.

CONCLUSION

It is concluded from this systematic literature search that a large number of different computer-assisted guided implant systems are available today in clinical practice. Differing levels and quantity of evidence were noted to be available, revealing a high mean implant survival rate of 96.6% after only 12 months of observation in different clinical indications. In addition, the mean percentage of intraoperative complications and unexpected events was 4.6%. The accuracy of these systems depends on all cumulative and interactive errors involved, from data-set acquisition to the surgical procedure. The meta-analysis of all preclinical and clinical studies revealed a total mean error of 0.74 mm at the entry point and 0.85 mm at the apex. Future long-term clinical data are necessary to identify clinical indications and to justify additional radiation doses, efforts, and costs associated with computer-assisted implant surgery. There is not yet evidence to suggest that computer-assisted surgery is superior to conventional procedures in terms of safety, outcomes, morbidity, or efficiency.

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APPENDIX

Review of Systems for Computer-Assisted Implant Dentistry

From information derived from review of the literature, combined with Internet searches and additional commercial sources, a compilation of computer-based products for implant surgery was created. It is important to clarify and distinguish the types of systems based on very specific definitions published in the *Glossary of Oral and Maxillofacial Implants* (GOMI; Chicago: Quintessence, 2007).

- ***Computer-aided design/Computer-assisted manufacture (CAD/CAM):*** Computer technology used to design and manufacture various components.
- ***Image guidance:*** General technique of using preoperative diagnostic imaging with computer-based planning tools to facilitate surgical and restorative plans and procedures.
- ***Imaging guide:*** Scan to determine bone volume, inclination and shape of the alveolar process, and bone height and width, which is used at a surgical l site.
- ***Surgical navigation:*** Computer-aided intraoperative navigation of surgical instruments and operation site, using real-time matching to the patients' anatomy. During surgical navigation, deviations from a preoperative plan can be immediately observed on the monitor.
- ***Computer-aided navigation****:* Computer systems for intraoperative navigation, which provide the surgeon with current positions of the instruments and operation site on a three-dimensional reconstructed image of the patient that is displayed on a monitor in the operating room. The system aims to transfer preoperative planning on radiographs or computed tomography scans of the patient, in real-time, and independent of the position of the patient's head.
- ***Surgical template:*** Laboratory-fabricated guide based on ideal prosthetic positioning of implants used during surgery. Also called *surgical guide*.
- ***Three-dimensional guidance system for implant placement:*** A computed tomography (CT) scan is performed to provide image data for a three-dimensional guidance construct for implant placement. A guide is a structure or marking that directs the motion or positioning of something, thus in implant dentistry this term should not be used as a synonym for *surgical implant guide*. A radiographic guide is rather used as a positioning device in intraoral radiography.

For the purpose of this consensus review, some GOMI definitions were clarified:

- ***Computer-guided (static) surgery****:* Use of a static surgical template that reproduces virtual implant position directly from computerized tomographic data and does not allow intraoperative modification of implant position.
- ***Computer-navigated (dynamic) surgery:*** Use of a surgical navigation system that reproduces virtual implant position directly from computerized tomographic data and allows intraoperative changes in implant position.

All systems incorporate planning of implant positions on a computer, using various software tools. These plans are then converted into surgical guides or used in other positioning systems in a variety of methods. In general, these implant positioning devices can be categorized into "static" and "dynamic" systems. "Static" systems are those that communicate predetermined sites using "surgical templates" or implant guides in the operating field. Therefore, "static systems" and "template-based systems" are synonymous. Alterations to implant position or deviations from the prefabricated template can be accomplished "free-hand".

Dynamic systems communicate the selected implant positions to the operative field with visual imaging tools on a computer monitor, rather than intraoral guides. The dynamic systems include "surgical navigation" and "computer-aided navigation" technologies. With these, the surgeon may alter the surgical procedure and implant position in real time using the anatomical information available from the preoperative plan and CT scan. Since the surgeon can see an avatar of the drill in a three-dimensional relationship to the patient's previously scanned anatomy during surgery, modifications can be accomplished with significantly more information. In essence, the navigation system provides a virtual surgical guide or template that may be altered when conditions indicate.

Table 8 is a compilation of currently available image guidance systems and those that appear to be in development or have some scientific publications available for review. The commercially available systems have been divided into two categories. The first section represents 22 software systems that are available for radiographic diagnosis and also generally provide for fabrication of surgical guides. The systems fall into the category of "three-dimensional guidance systems for implant placement," permitting implant planning from patient CT or CBCT scans. These products offer computer-based diagnostic and planning tools that permit enhancement, manipulation, and analysis of a patient's digital scan.

Table 8 Currently Available Systems in Computer-Assisted Implant Dentistry

Application	Website	Company	Virtual implant planning	Guide	Drill guide production	Notes
Surgical guides (static)						
3D-Doctor	www.ablesw.com	Able Software, USA	yes	Models	CDD	
Biodental Models	www.biomodel.com	BioMedical Modeling, USA	yes	Models	RP	
Implant3D	www.implant3d.com	Media Lab, Italy	yes	Models	RP	Create stereolithographic model
CyrtinaGuide	www.cyrtina.nl	Oratio, Netherlands	yes	Surgical guide	RP	
DentalSlice	www.bioparts.com.br	BioParts, Brazil	yes	Surgical guide	RP	
EasyGuide	www.keystonedental.com	Keystone Dental, USA	yes	Surgical guide	CDD	
GPIS		GPI Technology, Germany	Simplant/ IVS	Surgical guide	CDD	
ILS	www.tactile-tech.com	Tactile Technologies , Israel	yes	Surgical guide	Custom drilling tubes	Under development
ILUMA DigiGuide	www.imtec.com	IMTEC, USA	yes	Surgical guide	RP	Specific for MDI implants
Impla 3D	www.sdginnovations.com	Schutz Dental Group	yes	Surgical guide	CDD	
InVivoDental	www.anatomage.com	Anatomage , USA	yes	Surgical guide	CDD	Under development
AnatoModel	www.anatomage.com	Anatomage, USA	yes	Surgical guide	CDD	See EasyGuide
Implant 3D	www.med3d.de	Med3D, Switzerland	yes	Surgical guide	CDD	
Implant Master	www.ident-surgical.com	I-Dent Imaging, USA	yes	Surgical guide	RP	
Scan2Guide	www.ident-surgical.com	I-Dent Imaging, USA	yes	Surgical guide	RP	"Light" version of Implant Master
Ondemand3D Implant	www.cybermed.co.kr	Cybermed, Korea	yes	Surgical guide		
Oralim Oral Implant Planning System	www.medicim.com	Medicim, Belgium	yes	Surgical guide	RP	Marketed by Nobel Biocare
NobelGuide (Medicim Oralim)	www.nobelguide.com	Nobel Biocare, USA	yes	Surgical guide	CDD	Specific for Nobel Biocare implants
Simplant Master	www.materialise.com	Materialise Dental, Belgium	yes	Surgical guide	RP	
Simplant Planner	www.materialise.com	Materialise Dental, Belgium	yes	Surgical guide	RP	
Simplant Pro	www.materialise.com	Materialise Dental, Belgium	yes	Surgical guide	RP	
VIP	www.implantlogic.com	Implant Logic Systems, USA	yes	Surgical guide	CDD	Marketed by BioHorizons
Navigation systems (dynamic)						
VoNavix	www.codiagnostix.de	IVS Solutions, Germany	yes	Navigation	None	
Mona-Dent	www.imt-web.de	IMT, Germany	yes	Navigation	None	
NaviBase,NaviDoc & NaviPad	www.robodent.com	Robodent, Germany	yes	Navigation	None	
Treon (medical)	www.medtronicnavigation.com	Medtronic Navigation, USA	yes	Navigation	None	Not commercially available
IGI	www.image-navigation.com	Image Navigation, Israel	yes	Navigation	None	Formerly DenX, Inc
VISIT		University of Vienna, Austria		Navigation	None	not commercially available

RP = rapid prototyping; CDD = computer-driven drilling.

Planning information can remain stored on a computer in digital files for visual review or can be sent to a manufacturing facility to create three-dimensional models of the stored images. Most systems generate information to fabricate a surgical guide once appropriate surgical planning has been completed. This manufacturing process, generically called CAD/CAM, uses either rapid prototyping technologies such as 3D printing and stereolithography or "computer-driven drilling (CDD)" to create anatomical models.[41]

For surgical planning, implant avatars are positioned into the scanned images using software to simulate surgical placement. Once a satisfactory plan is approved and saved, CAD/CAM technology is used to produce a customized surgical template or guide. Depending on the manufacturer, guides can be indexed to available surrounding teeth, mucosal contours, or bony contours. Some manufacturers additionally offer prosthesis fabrication, combining the digital information with dental prosthetics.

Advantages of these systems may include general familiarity with the use of surgical guides based on long-established procedures. A high degree of precision may be obtained, particularly when guides incorporate graduated dimensions of drilling sleeves to guide increasing diameters of drills. Some systems provide two-dimensional (mesiodistal and buccolingual) guidance, while others also incorporate depth control. The precision of the surgical templates depends on the accuracy of the scan and the fit of the device during use. Some manufacturers require casts of the patients' arches or teeth to insure accurate fit, while others create the guides from the scanned images and contours. Difficulties can arise when patients have poor edentulous ridge form or loose teeth, or extractions are anticipated, since anatomical landmarks required for surgical guide stabilization could move or change. Several strategies to overcome these problems have been devised. As previously noted, some manufacturers fabricate provisional or final restorations from the digital plans, but there are too few long-term data to permit considering this a routine or accepted procedure.

The final group of devices includes six surgical navigation systems, four of which are commercially available. Surgical navigation systems require that sensors be attached to both the patient and the surgical handpiece. These sensors transmit three-dimensional positional information to a camera or detector that allows the computer to instantaneously calculate and display the virtual position of the instruments relative to the stored image of the patient's anatomy. An analogous technology is the global positioning system used for personal transportation, which similarly uses a satellite to track an individual's movements against a previously stored map. During surgery, the surgeon typically watches the computer monitor in addition to, or instead of, the surgical site to monitor positional accuracy. In medicine, this is similar to endoscopic or laparoscopic procedures, where the surgical sites are obscured, requiring viewing on a monitor.

An advantage of navigation systems is that the surgical plan can be altered or modified while retaining the "virtual vision" of the technology. The surgeon can either move the virtual implant on the plan or ignore the plan completely and use the navigation system to contemporaneously visualize the patient's anatomy. This permits the surgeon to steer around obstacles, defects, or conditions that were not apparent on the presurgical scan. Similar technology has been safely and effectively used in other branches of medicine, including neurosurgery, spinal surgery, and cardiac surgery. In addition to the stability problems noted for surgical guides, complications and difficulties can arise with navigation if the sensors are not precisely and firmly attached to the patient or handpiece. To date, restorations have not been CAD/CAM produced from planning files of the navigation systems. It is possible to do a sham procedure on dental casts, so that a dental laboratory could prefabricate restorations for immediate-loading procedures prior to implant placement. As with restorations planned from computer-generated surgical guides, this technique has not been adequately investigated.