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Review article

The accuracy of implant placement with computer-guided surgery in partially edentulous patients and possible influencing factors: A systematic review and meta-analysis

Ramadhan Hardani Putra[a,b], Nobuhiro Yoda[a,*], Eha Renwi Astuti[b], Keiichi Sasaki[a]

[a] *Division of Advanced Prosthetic Dentistry, Tohoku University Graduate School of Dentistry, Japan*

[b] *Department of Dentomaxillofacial Radiology, Faculty of Dental Medicine, Universitas Airlangga, Indonesia*

Abstract

Purpose: To review the current clinical studies regarding the accuracy of implant computer-guided surgery in partially edentulous patients and investigate potential influencing factors.

Study selection: Electronic searches on the PubMed and Cochrane Central Register of Controlled Trials databases, and subsequent manual searches were performed. Two reviewers selected the studies following our inclusion and exclusion criteria. Qualitative review and meta-analysis of the implant placement accuracy were performed to analyze potential influencing factors. Angular deviation, coronal deviation, apical deviation, and depth deviation were evaluated as the accuracy outcomes.

Results: Eighteen studies were included in this systematic review, including six randomized controlled trials, nine prospective studies, and three retrospective clinical studies. A total of 1317 implants placed in 642 partially edentulous patients were reviewed. Eight studies were evaluated using meta-analysis. Fully guided surgery showed statistically higher accuracy in angular ($P < 0.001$), coronal ($P < 0.001$), and apical deviation ($P < 0.05$) compared with pilot-drill guided surgery. A statistically significant difference ($P < 0.001$) was also observed in coronal deviation between the bounded edentulous (BES) and distal extension spaces (DES). A significantly lower angular deviation ($P < 0.001$) was found in implants placed using computer-aided design/computer-aided manufacturing (CAD/CAM) compared to the conventional surgical guides.

Conclusions: The edentulous space type, surgical guide manufacturing procedure, and guided surgery protocol can influence the accuracy of computer-guided surgery in partially edentulous patients. Higher accuracy was found when the implants were placed in BES, with CAD/CAM manufactured surgical guides, using a fully guided surgery protocol.

Keywords: *Accuracy, Dental implant, Computer guided surgery, Partially edentulous*

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1. Introduction

The introduction of computed tomography (CT) imaging in implant dentistry, including cone beam CT (CBCT) and multi-slice CT (MSCT), has improved dental implant treatment outcomes by allowing three-dimensional (3D) bone geometry analysis for performing the pre-surgical implant placement planning.[1, 2] Computer-guided (static) and computer-navigated (dynamic) surgical systems have been introduced to transfer a simulated pre-operative implant position from planning software into the surgical field. The difference between the two systems is that the static systems in computer-guided surgery apply a static surgical guide or template made through a laboratory process, whereas the dynamic or computer-navigated systems use the mechanical or optical system to display the process on a real-time monitor.[3] Currently, static system surgery has been more often applied in clinical practice than the dynamic system because it involves a lower initial cost. Static surgical guides can be made using 3D printing systems associated with computer-aided design/computer-aided manufacturing (CAD/CAM) technology, or manual modification of the radiographic scan appliance on the cast model.[4] Therefore, implant placement using computer-guided surgery provides shorter surgical duration, less discomfort to the patient, and adequate implant placement than freehand implant surgery. [5, 6]

To date, implant placement accuracy with computer-guided surgery has been reported in many studies. The term "accuracy" has been assessed by the deviation between the virtually planned and actually placed implant position. This deviation can occur due to numerous contributing factors. During implant-guided surgery through a relatively long process, errors in each step may accumulate, resulting in deviations in the actual implant position.[4, 7] These errors may be generated from technical and/or human errors. [8, 9]

In partially edentulous patients, various protocols from planning to surgery have been introduced in many studies. As the error source in each protocol can be different, it is important to understand how each step in computer-guided surgery could lead to implant placement inaccuracies and evaluate the contributing factors. Several well-written systematic reviews have described the factors contributing to the implant placement accuracy. [10–12] Although the accuracy rates of computer-guided implant surgery

* Corresponding author at: Division of Advanced Prosthetic Dentistry, Tohoku University Graduate School of Dentistry 4-1, Seiryo-machi, Sendai, Miyagi, 980-8575 , Japan.

E-mail address: nobuhiro.yoda.e2@tohoku.ac.jp (N. Yoda).

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in fully edentulous patients have already been systematically reviewed,[13] there are no specific systematic reviews regarding factors influencing the implant placement accuracy with computer-guided surgery in partially edentulous patients.

There are fundamental differences in the protocol based on the surgical guide support mechanism between partially and fully edentulous patients, which can affect the implant placement accuracy,[4] and several studies have also demonstrated different accuracy outcomes.[14,15] Additionally, partially edentulous condition variations, including those indicated by the Kennedy classification, may also influence the outcome. Hence, our aim was to systematically review the current clinical studies concerning the accuracy of implant computer-guided surgery, particularly in partially edentulous patients, and to elucidate the potential influencing factors to justify the clinical indication for computer-guided surgery.

2. Materials and methods

2.1. Protocol and registration

This review was registered at the International Prospective Register of Systematic Review (PROPERO) of the National Institute of Health Research (registration number CRD42020183234). This review was reported according to the "Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)" guidelines.[16]

2.2. Population, Intervention, Comparison, Outcome question

The focused Population, Intervention, Comparison, Outcome (PICO) question was "what factors can affect the result of implant placement accuracy with computer-guided surgery in partially edentulous patients?" The question was used to construct the search strategy as follows: P = Partially edentulous patient treated with dental implant; I = Implant placement using computer-guided surgery; C = Pre-operative planned implant on software; O = Accuracy of implant placement.

2.3. Search strategy

An electronic literature search, limited to English language studies published between 2008 and March 2020, was performed using the PubMed and Cochrane Central Register of Controlled Trials (CENTRAL) databases. In addition, a manual search through the reference lists of eligible studies was also performed. Randomized controlled trials (RCTs), prospective, and retrospective clinical cohort studies were included. Previous systematic reviews have shown that studies prior to 2008 reported varying accuracy outcomes, which probably resulted from the limited technology at that time.[17]

The following search terms were utilized for an electronic search of the databases: (dental implantation or dental implant) and (computer-assisted surgery or computer-aided design or computer-aided surgery or computer-guided surgery or digital dentistry or guided implant surgery) and (dimensional measurement accuracy or dental implant deviation or dental implant accuracy or dental implant precision).

2.4. Study selection

Two reviewers screened the title and abstract of the relevant articles from the electronic search independently. Next, full-text screening was performed to decide whether each article met the inclusion criteria. The exclusion criteria were recorded. Any disagreements were resolved by mutual discussion between the reviewers. A third reviewer made the selection when there was disagreement between the two reviewers.

This review included studies in which computer-guided (static) surgery was performed in more than 10 partially edentulous patients. Studies, including fully edentulous patients with sufficient outcomes and evaluation of partially edentulous patients were considered eligible for inclusion. The accuracy parameter included at least angular deviation, coronal deviation at the entry point, and apical deviation at the implant apex.

Excluded from this review were studies that performed computer-navigation (dynamic) surgeries; including only fully edentulous, or both fully and partially edentulous patients with insufficient outcomes; systematic reviews, case reports, in vitro, and cadaver studies; articles with duplicated populations from the same author; and studies with insufficient data and information of the accuracy outcome.

2.5. Data collection process

The first and second authors extracted and checked the data from the articles, respectively. The extracted data were recorded on an Excel spreadsheet (Microsoft Corp., Redmond, WA, USA) as follows: author, study year, study design, total sample, arch type, edentulous space type, implant position, implant planning software, optical scanning, surgical guide fabrication, surgical protocol, and accuracy measurement methods. Data related to the accuracy were extracted as follows: angular deviation, implant coronal deviation, implant apical deviation, and depth deviation.

The data were further analyzed by comparing the two groups on the basis of the following factors:

1. The arch.
   The accuracy of implant placed in the maxillary and mandibular arches were compared.
2. The edentulous spaces.
   The accuracy of the implant placed in bounded (BES) and distal extension edentulous spaces (DES) were compared. The BES and DES correspond to conditions when the teeth or implants remain on each side of the space,[18] and when the space is located posteriorly to the most distal tooth or implant abutment, respectively.
3. The surgical guide fabrication method.
   The accuracy of implant placement with the surgical guide fabricated by the conventional and CAD/CAM methods were compared. The conventional method is to produce a surgical guide through a dental laboratory process using a mechanical positioning device or drilling machines by modifying a radiographic scan appliance. The CAD/CAM method involves manufacturing the surgical guide using 3D printing, i.e., stereolithographic surgical guide.
4. The computer-guided surgery protocol.
   The accuracy of implant placement with pilot-drill and fully guided protocols was compared. The pilot-drill guided protocol used the surgical guide only in the initial drill of the osteotomy, whereas the fully guided protocol used the surgical guide from osteotomy to implant placement.

2.6. Risk of bias in included studies

The Newcastle–Ottawa Scale adapted by Chambrone et al. was used to assess the risk of bias in the prospective and retrospective studies.[19, 20] A maximum of 13 points could be assigned for each included study; studies with 10–13, 7–9, or lower points indicated high, medium, and low methodological quality, respectively. The recommendations for systematic reviews of the Cochrane collaboration interventions were followed to evaluate the risk of bias of the included RCTs.[21]

2.7. Outcome measurement

The deviation between the planned and actual placed implants was measured as an outcome. The means and standard deviations of the following parameters were calculated for assessment of the implant placement accuracy: (Fig. 1)

a. Angular deviation (measured in degrees): an angulation between the longitudinal axes of the planned and actual placed implants.

b. Coronal deviation (measured in mm): a linear deviation between the entry point (i.e., the center of platform) of the planned and actual placed implants.

c. Apical deviation (measured in mm): a linear deviation between the apex point of the planned and actual placed implants.

d. Depth deviation (measured in mm): a linear deviation measured in the vertical direction between the platform center of the planned and actual placed implants.

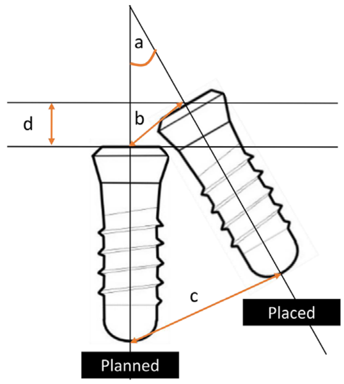

Fig. 1. The accuracy parameter of implant placement. (a) angular deviation, (b) coronal deviation, (c) apical deviation, (d) Depth deviation.

2.8. Statistical analysis

Meta-analyses were performed using the random-effect model to evaluate the following factors: arch type, edentulous space type, surgical guide fabrication, and guided surgery protocol. The linear model of the random effects considered the continuous data, expressed as the pooled weighted mean difference for each outcome variable and the associated 95% confidence intervals (CIs).

Heterogeneity between studies was assessed using I^2 statistics and Cochran's Q test. P-values and 95% CIs were calculated for each variable of interest.[22] A P-value <0.05 was considered statistically significant. I^2 values of 25%, 50%, and 75% corresponded to the cut-off points for low, moderate, and high degrees of heterogeneity, respectively. Analyses were conducted using Review Manager version 5.3 (Cochrane Tech., Troy, MI, USA).

3. Results

After the initial search, 1292 article titles and abstracts were identified. Of these, 1241 articles were excluded after analysis, and finally, the reviewers shortlisted 51 articles. After evaluation of the full articles, 33 were excluded and 18 studies met our inclusion criteria (Fig. 2).

3.1. Study characteristics

The characteristics of the included articles are presented in Table 1. A total of 642 patients and 1317 implants were analyzed in six RCTs,[23–28] nine prospective studies, [15, 29–36] and three retrospective studies.[37–39]. Six patients were excluded from the studies for the following reasons: insufficient bone width and the need for bone augmentation,[33] fracture of buccal bone during implant insertion, fracture of the insertion driver inside the implant during its installation, and patient drop out after enrolment.[23] In addition, failures in 11 implants in total were reported as follows: loss of implants due to infection and after the follow-up period, [32] limited mouth opening,[33, 36] buccal dehiscence, and implant mobility after follow-up.[33] A total of 65 implants from Ersoy et al. were excluded, as they were performed in fully edentulous patients;[15] however, nine and 20 implants placed in the single tooth loss and distal extension spaces, respectively, were included in the meta-analysis.

Three techniques were used in the included studies to transfer the intraoral condition into implant planning software. Ten, six, and four studies used extra-oral scanning procedures (e.g., optical scanning of the master cast), intraoral scanning, and radiographic scan appliance with radiopaque markers instead of using an optical scanner, respectively. Most studies focused on the CAD/CAM surgical guide instead of the laboratory-based procedure for fabricating the surgical guide. Only four studies used the surgical guide that was modified from the radiographic scan appliance, which was fabricated by a dental technician using the laboratory device.

Various flap methods at the implant placement surgery were performed

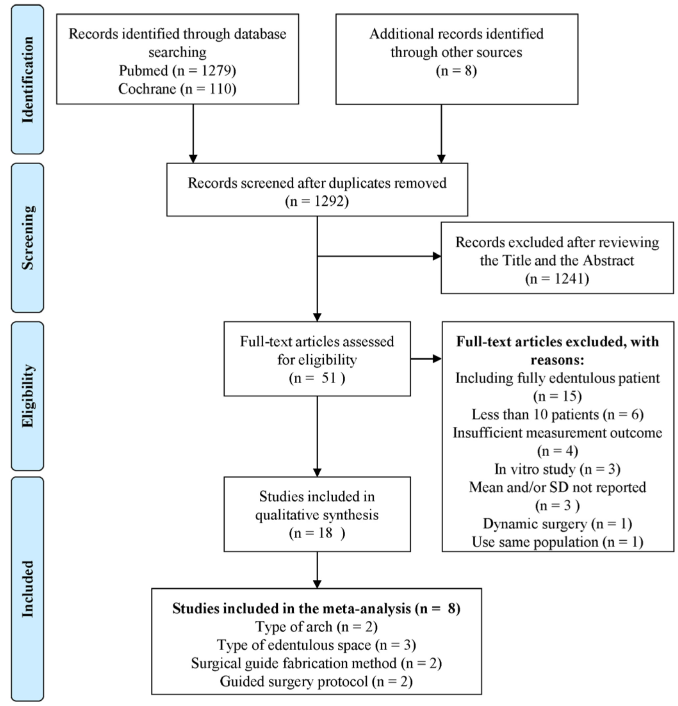

Fig. 2. Flow diagram of articles found through databases.

in the included studies. Thirteen studies used tooth-supported surgical guides and fully guided protocols. Only two studies used surgical guides with stabilization screws.[28, 36] Eight studies assessed the implant placement accuracy using radiographic methods, which compared the pre-operative and post-operative CT images. Conversely, six studies assessed accuracy using non-radiographic methods, in which two and four studies evaluated the actual placed implant using scanned post-surgical impression and intraoral optical scanning of the inserted implant, respectively. Both radiographic and non-radiographic methods were compared in four studies. Three studies compared the radiographic method with scanned post-surgical model analysis, and one study with intraoral scanning of the actual placed implant. For the implant placement accuracy parameters, four studies reported only horizontal deviation instead of linear/global deviation.[28, 35–37] Therefore, these studies were excluded from our meta-analysis. Only eight studies reported depth deviation. Thus, meta-analysis was not performed on this parameter.

3.2. Risk of bias result

The risk of bias assessment showed that the observational studies (prospective and retrospective) included in this systematic review received 8–11 points, indicating a medium and high level of methodological quality (Fig. 3). Six RCTs presented low risk for random sequence generation, allocation concealment, blinding of outcome assessment, and other possible causes of bias. Among these RCTs, three studies had unclear bias in participant and personal blinding, as the surgeon in these studies was involved in planning the implant position, even if it may not have affected the outcome. One study showed unclear bias in incomplete outcome data, as it was reported that implant failure may be due to an error of guided implant surgery, but it may not have affected the overall outcome assessment. One study had unclear bias in selective reporting because horizontal deviation was reported instead of linear/global deviation, and thus, was excluded from the meta-analysis (Fig. 4).

3.3. Effect of the arch (maxillary vs. mandibular arch)

Two prospective studies (n = 210 implants) were reviewed to compare the accuracy of guided surgery performed on the maxillary or mandibular

Table 1. Characteristics of studies included for qualitative and meta-analysis.

No	Author	Year	Study design	Total sample			Clinical condition			Planning / pre-operative			Surgical procedure			Evaluation
				Patient	Implant	Failure	Type of arch	Edentulous spaces	Implant position	Optical scanning	Surgical guide type	Software	Flap method	Guide support	Surgical protocol	Method
1	Ersoy	2008	Prospect	21	94	0	Max (48) Man (46)	BES (9) DES (29)	NR	No	CAD/CAM	Stentcad	Flap (53) Flapless (41)	Tooth (26) Mucosa (23) Bone (45)	Fully	Radiographic
2	Behneke	2011	Prospect	52	132	0	Max (87) Man (45)	BES (43) DES (52)	NR	No	Laboratory	Med3D	Flap (66) Flapless (66)	Tooth	Fully (24) Half (108)	Radiographic
3	Farley	2013	Prospect	10	20	0	Man	BES – STL	Post	No	Laboratory (10) CAD/ CAM (10)	I-dent	Flap (10) Flapless (10)	Tooth	NR	Radiographic
4	Alzoubi	2016	Retro	20	25	0	Max;man	NR	Ante (11) Post (29)	IOS	CAD/CAM	Anatomage	NR	Tooth	NR	Radiographic (25) Non radiographic (9)
5	Schnutenhaus	2016	Retro	24	24	0	Max;man	BES (12) DES (12)	Ante; post	EOS	CAD/CAM	SMOP	Flap Flapless	Tooth	Fully	Non-radiographic
6	Cristache	2017	Prospect	25	65	0	Max (32) Man (33)	NR	Ante; post	EOS	CAD/CAM	R2gate	Flapless	Tooth	Fully	Non-radiographic
7	Schnutenhaus	2018	Retro	56	122	0	Max (48) Man (74)	BES (42) DES (80)	NR	EOS	CAD/CAM	SMOP	Flap Flapless	NR	Fully	Non-radiographic
8	Ma	2018	Prospect	26	28	0	Max;man	NR	Post	EOS	CAD/CAM	In2guide	Flapless	NR	Fully	Radiographic (28) Non radiographic (28)
9	Younes	2018	RCT	33	71	0	Max	BES (25) DES (46)	Post	EOS	CAD/CAM	Simplant	Flapless	Tooth	Pilot-drill (24) Fully (21)	Radiographic
10	Skjerven	2019	Prospect	13	28	3 imp	Max (15) Man (13)	BES and DES	Ante; post	No	Laboratory	CoDiagnostix	Flap (26) Flapless (2)	Tooth	Fully	Radiographic (26) Non radiographic (26)
11	Derksen	2019	Prospect	68	149	2 px; 4 imp	Max (66) Man (79)	BES (81) DES (64)	NR	IOS	CAD/CAM	CoDiagnostix	Flap (111) Flapless (34)	Tooth	Fully	Non-radiographic
12	Tang	2019	Prospect	19	32	0	NR	NR	NR	EOS	NR	NR	NR	NR	NR	Radiographic Non-radiographic
13	Tallarico (a)	2019	Prospect	39	119	4 imp	Max (65) Man (54)	NR	Ante (32) Post (87)	IOS	CAD/CAM	3Diagnosys	Flap Flapless	NR	NR	Non-radiographic
14	Tallarico (b)	2019	RCT	20	57	0	Max (33) Man (24)	NR	Ante;post	IOS (28) EOS (29)	CAD/CAM	3Diagnosys	Flap Flapless	NR	Fully	Non-radiographic
15	Smitkarn	2019	RCT	52	60	0	Max (20) Man (10)	STL	Ante (5) Premolar (9) Molar (16)	IOS	CAD/CAM	CoDiagnostix	Flap	Tooth	Fully	Radiographic
16	Magrin	2020	RCT	16	24	4 px	Man	BES – STL	Post	EOS	Laboratory (12) CAD/ CAM (12)	Dentaslice	Flap (12) flapless (12)	Tooth	NR	Radiographic
17	Varga	2020	RCT	101	207	0	Max (70) Man (137)	BES and DES	Ante; post	EOS	CAD/CAM	Smart guide	Flap	Tooth	Pilot-drill (49) Fully (52)	Radiographic
18	Kiatkroekkrai	2020	RCT	47	60	0	Max (40) Man (20)	NR	Ante (13) Post (47)	IOS (30) EOS (30)	CAD/CAM	CoDiagnostix	Flap Flapless	Tooth	Fully	Radiographic

RCT, Randomized controlled trial; Prospect, prospective study; Retro, retrospective study; Imp, implant; Px, patient; Max, maxillary; Man, mandibular; Ante, anterior; Post, posterior; BES, Bounded edentulous space; DES, Distal extension space; STL, Single tooth loss; NR, Not reported; CAD/CAM, computer-aided design/computer-aided manufacturing.

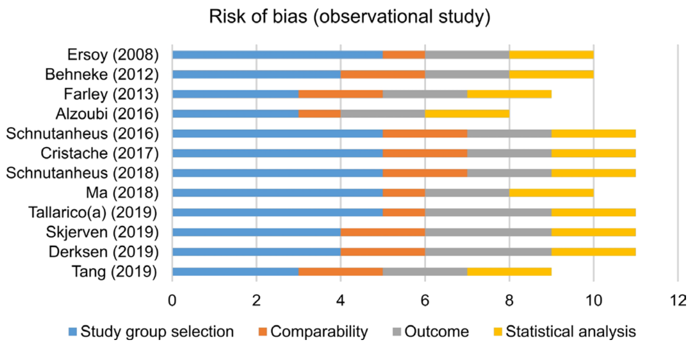

Fig. 3. Risk of bias score of observational (prospective and retrospective) studies.

arch.[30,33] The meta-analysis results showed no statistical significance (P >0.05) in angular (mean difference [MD]: -0.02 [95% confidence interval (CI): -0.54–0.51]; Fig. 5a), coronal (MD: 0.10 [95% CI: -0.23–0.43]; Fig. 5b), and apical deviations (MD: 0.13 [95% CI: -0.39–0.66]; Fig. 5c) when comparing the maxillary and mandibular arches. A medium degree of heterogeneity between the studies was observed on angular deviation (P >0.05; I^2 = 0.68). A high degree of homogeneity between the studies was found on coronal (P <0.05; I^2 = 0.84) and apical deviation (P <0.05; I^2 = 0.91).

3.4. Effect of edentulous space (BES vs. DES)

Three studies (two prospective and one retrospective studies; n = 305 implants) were reviewed to compare the accuracy of guided surgery performed on the BES and DES.[15,33,38] Statistically significant differences (P <0.001) were found in the mean coronal deviation between the BES and DES (MD: -0.21 [95% CI: -0.36–0.07]; Fig. 6a). The meta-analysis results showed no statistical significance (P >0.05) in angular deviation when comparing the edentulous spaces (MD: -0.42 [95% CI: -1.00–0.16]; Fig. 6b), whereas differences in apical deviation between the BES and DES were also not statistically significant (P >0.05) (MD: -0.43 [95% CI: -0.90–0.04]; Fig. 6c). A low degree of homogeneity between the studies was observed on angular (P >0.05; I^2 = 0.38) and coronal deviations (P >0.05; I^2 = 0.31). A high degree of heterogeneity between the studies was found in apical deviation (P <0.05; I^2 = 0.89).

3.5. Effect of surgical guide fabrication method (CAD/CAM vs. conventional)

Two studies (one prospective study and one RCT; n = 22 implants) were reviewed to compare the accuracy of guided surgery performed using CAD/CAM or conventional methods.[23,29] Statistically significant differences (P <0.001) were found in the mean angular deviation between the CAD/CAM and the conventional surgical guide (MD: 1.45 [95% CI: 0.42–2.47]; Fig. 7a). The meta-analysis results showed no statistically significant differences (P >0.05) in coronal and apical deviations when comparing the CAD/CAM and conventional surgical guides (MD: 0.08 [95% CI: -0.85–1.01]; Fig. 7b and MD: 0.19 [95% CI: -0.85–1.23]; Fig. 7c, respectively). No heterogeneity was observed between the studies on angular deviation (P >0.05; I^2 = 0). A medium degree of homogeneity between the studies was found on the platform (P >0.05; I^2 = 0.67) and apical deviation (P >0.05; I^2 = 0.67).

3.6. Effect of guided surgery protocol (pilot-drill vs. fully guided)

Two RCT studies (n = 146 implants) were reviewed to compare the accuracy of guided surgery performed using different protocols.[25,26] Statistically significant differences (P <0.001) were found for all accuracy parameters. The mean angular deviation between the pilot-drill and fully guided surgeries (MD: 2.83 [95% CI: 1.82–3.85]; Fig. 8a), coronal deviation (MD: 0.29 [95% CI: 0.07–0.50]; Fig. 8b), and apical deviation

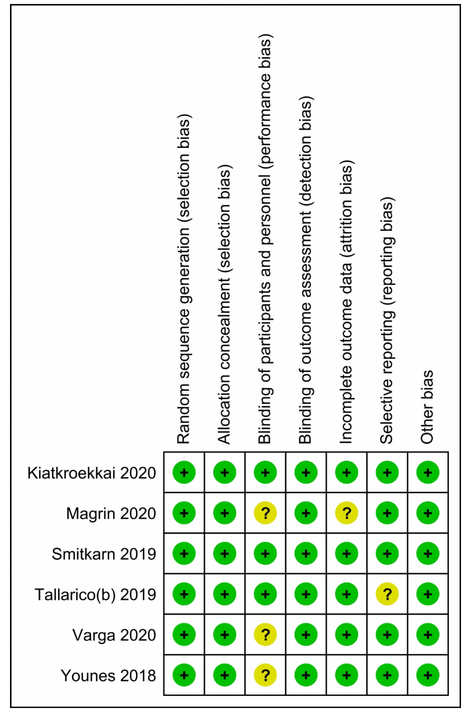

Fig. 4. Risk of bias of RCT studies. (+) low risk of bias, (?) unclear risk of bias, (-) high risk of bias.

(MD: 0.19 [95% CI: 0.04–0.62]; Fig. 8c) were significantly different when comparing the pilot-drill and fully guided surgeries. No heterogeneity between the studies was observed on angular (P >0.05; I^2 = 0), coronal (P >0.05; I^2 = 0.12), and apical deviation (P = 0.05; I^2 = 0).

4. Discussion

This systematic review analyzed the possible factors that influence the accuracy of implant placement using computer-guided surgery. The implant placement accuracy could be affected by the fundamental differences between partially and fully edentulous patients.[4, 14, 15] Additionally, different supporting tissues in the surgical guide can affect the outcome between both edentulous patients, as tooth-supported surgical guides are generally used for partially edentulous patients, whereas mucosa- or bone-supported surgical guides are used for fully edentulous patients. Gallardo et al. concluded that the supporting tissues for surgical guidance influenced the accuracy of computer-guided surgery in their meta-analysis.[40] Thus, our review only focused on partially edentulous patients.

Our study excluded in vitro and ex vivo studies as they might be an underestimate of error and overestimate of accuracy due to the lack of limitations, leading to confounding factors, such as limited mouth opening, saliva, bleeding, mucosal resilience, and bone density.[41] The accuracy of computer-guided surgery can be sensitive to cumulative errors. The inaccuracies or deviations in implant placement were reflected by the sum of technical errors during the examination, planning, surgical guide manufacturing, and surgical procedure. Clinical factors, such as patients' intraoral condition, can also affect the implant deviation.[11] Therefore, clinicians should be aware of and understand each factor that can potentially influence the implant placement accuracy in the current workflow sequence for computer-guided surgery.

The first potential influencing factor of the implant deviation can occur when performing CT scans, which can be obtained through MSCT or CBCT scans. In association with computer-guided surgery, CBCT has gained popularity in implant dentistry due to its compact design, lower radiation exposure, lower cost, and shorter scanning time compared to MSCT. On the other hand, MSCT can assess structure and tissue based on CT density value accurately compared to CBCT because density value is

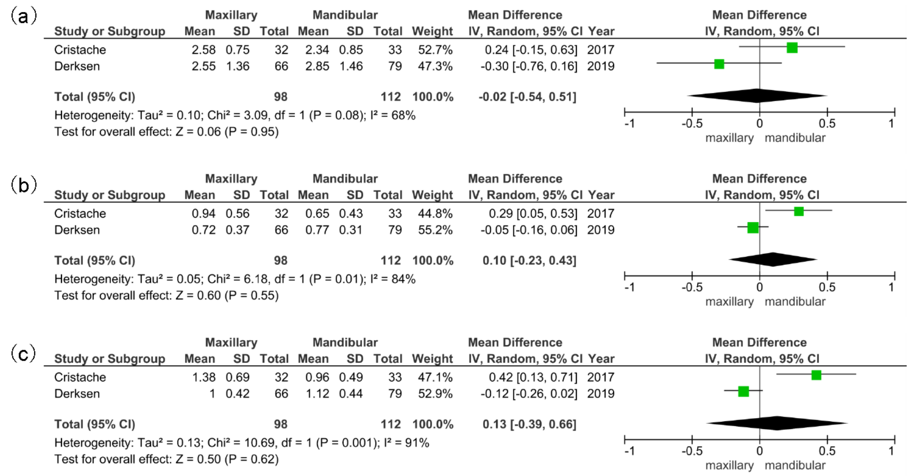

Fig. 5. Forest plot evaluating the effects of the arch (maxillary vs mandibular arch); (a) angular deviation; (b) coronal deviation; and (c) apical deviation.

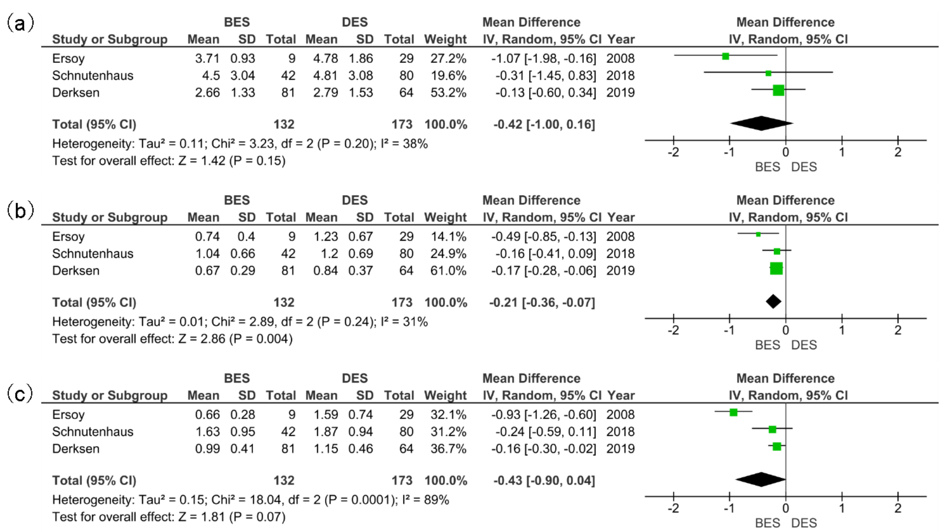

Fig. 6. Forest plot evaluating the effects of edentulous space (BES vs DES); (a) angular deviation; (b) coronal deviation; and (c) apical deviation.

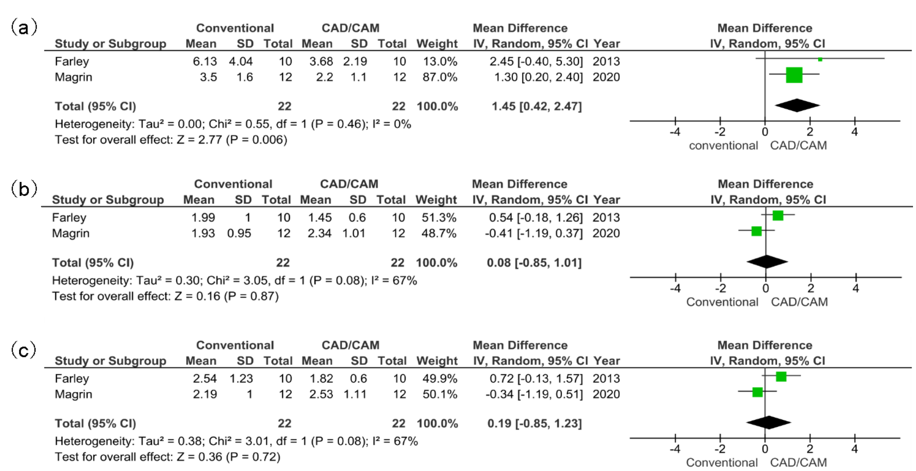

Figure 7
Forest plot evaluating the effects of surgical guide fabrication method (conventional vs CAD/CAM); (a) angular deviation; (b) coronal deviation; and (c) apical deviation

Fig. 7. Forest plot evaluating the effects of surgical guide fabrication method (conventional vs CAD/CAM); (a) angular deviation; (b) coronal deviation; and (c) apical deviation.

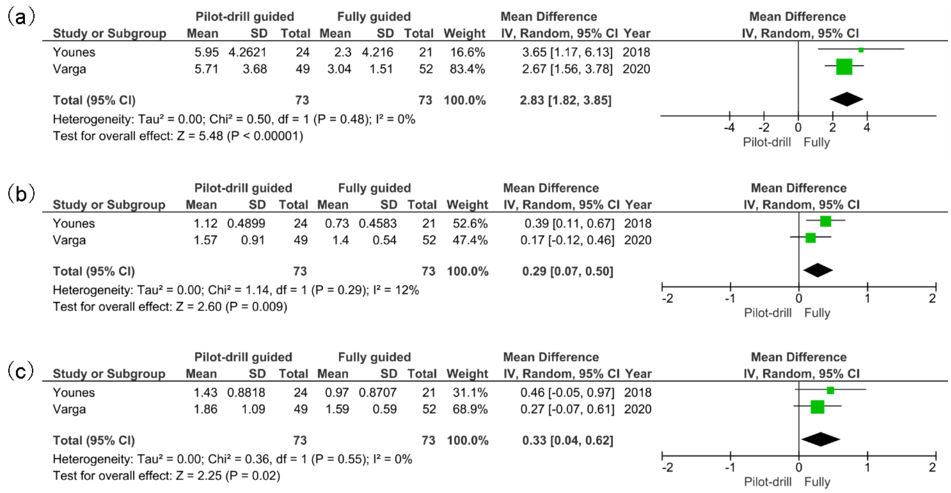

Fig. 8. Forest plot evaluating the effects of guided surgery protocol (pilot-drill vs fully guided); (a) coronal deviation; (b) platform deviation; and (c) apical deviation.

not calibrated for use with CBCT imaging data volumes. Regardless of the different modalities, the clinical studies suggested that a similar accuracy outcome could be obtained when comparing the preoperative planning using the MSCT and CBCT.[1, 2, 11] However, Pettersson et al. demonstrated that the patient movement factor during CT scanning could cause greater angular deviation in the implant placement.[42] Such motion artifacts could cause image distortion and quality degradation. In this case, CBCT may have some advantages owing to the shorter scanning time than conventional CT, resulting in reduced patient movement risk. Metallic artifact, which is a large spike emanating from around the teeth, can also distort the bone in the local area. These artifacts lead to difficulties in marker identification and precise transfer of virtual planning to the surgical site.[43] Thus, these errors may indirectly affect the workflow of implant planning and surgical guide plate fabrication.

Along with CT scan data, intraoral conditions are also transferred into implant planning software. Optical scanning has been generally performed to acquire the STL data of the remaining teeth and soft-tissue morphology. The STL data can be acquired from the extraoral scanning (EOS) of the cast model or from digital intraoral scanning (IOS). Nowadays, many studies have introduced the use of IOS to perform a fully digital workflow of computer-guided surgery, especially in partially edentulous patients. Two RCTs that compared the implant placement accuracy between the IOS and EOS methods in partially edentulous patients who had single-tooth loss [27] and at least 5 residual teeth [28] were analyzed in our reviews. Both RCTs reported equal accuracy outcomes between the IOS and EOS methods. Therefore, both methods can be utilized for planning computer-guided implant surgery in partially edentulous patients. However, potential errors from both methods are still susceptible for various reasons. Impression distortion,[44, 45] which could be replicated by the EOS procedure, can result in inaccuracy of the STL produced. On the other hand, several studies have also reported a potential error of IOS, such as intraoral condition,[46] scanner displacement,[47] and operator experience.[48]

After virtual determination of the ideal implant positions using the planning software, a surgical guide was produced to place the implant according to the planned position. The surgical guide can be produced by conventional methods or CAD/CAM technology. The “conventional guide” was produced in a dental laboratory using a mechanical positioning device or drilling machines by modifying a radiographic scan appliance into a surgical guide.[49, 50] In our meta-analysis, two split-mouth randomized clinical trial studies were included,[23, 29] which compared the implant placement accuracy between the conventional and CAD/CAM surgical guides in a single-BES. The results indicated a higher angular deviation provided by the conventional than by the CAD/CAM guides. During the fabrication of conventional surgical guides, human error may contribute to inaccuracy in the manual procedure when making the drilling holes. The transformation of the radiographic template into a surgical guide can be a highly technique-sensitive and time-consuming manual process, in which the handling of the laboratory device (drilling machine) is probably the most important factor.[34] It should be noted that these findings were obtained by investigating 22 single implants in our meta-analysis. These preliminary results should be confirmed by performing clinical studies with a larger patient population and more implants.

The patients’ clinical condition, such as the type of dental arch, implant position, and edentulous spaces, were analyzed in this study. Our meta-analysis showed no significant differences in implant placement accuracy between the maxillary and mandibular arches. Additionally, three studies[24, 35, 36] that were included in our systematic review also demonstrated similar results in terms of implant placement accuracy between both arches. Although Behneke et al. reported significant differences in the apical deviation between the maxillary and mandibular arches, they stated that the result had no clinical meaning because it was only a 0.1 mm difference.[35] In contrast, a meta-analysis by Zhou et al., which included both partially and fully edentulous patients, demonstrated that better angular accuracy was shown in the cases of computer-guided surgery on the mandible compared to those on the maxilla.[11] The conflicting results could be explained by the different patient selections. Focusing only on the partial edentulous cases, the arch type did not influence the accuracy outcomes.

Meta-analysis could not be performed to analyze the influence of implant position on the placement accuracy because different outcome measurements were reported in two included studies.[24, 36] Smitkarn et al. demonstrated that there were no significant differences in the accuracy outcomes when implant was located in the anterior, premolar, or molar region.[24] In contrast, Tallarico et al., who compared different types of sleeve-designed surgical guides, found that the accuracies were significantly lower in the posterior site than in the anterior site in terms of angular and horizontal deviation. They described that the decrease in accuracy in the case of implant placement in the posterior site could be caused by the use of an open sleeves surgical guide, which allowed the drills to move horizontally.[36] Limitation of mouth opening may also interfere with the surgery process and can adversely affect the accuracy of implant placement, especially in the posterior site. [35, 41] Interpretation of the results from the above studies was restricted by different study designs; therefore, conclusions could not be derived. Future studies are required to verify these contrasting results.

There are several classifications of partially edentulous spaces. Three studies included in our meta-analysis originally classified edentulous spaces, as follows: single BES and uni- or bilateral DES;[15] single BES, multiple BES, uni-, and bilateral DES;[38] BES and DES (next to the tooth, implant, and dummy).[33] In our meta-analysis, simplified two edentulous spaces (BES and DES), regardless of the implant number and the affected side, were employed. The forest plot (Fig. 5) shows a better accuracy in BES than in DES in any outcome. Behneke et al. also observed less significant deviation in the coronal, apical, and angular deviations in a single BES compared to bilateral DES, multiple BES, and a combination of both conditions.[35] In contrast, Schnutanheus et al. found that there was no significant difference in angular, depth, and horizontal deviation between the single BES and DES.[37] Our results suggested that implant placement in BES showed better accuracy when compared with DES. These differences could be explained by the supporting tissues of the surgical guide. Gallardo et al. concluded that the tooth-supported surgical guide was more accurate than the bone and mucosa-supported guides.[40] Supports of the mesial and distal teeth can provide better stability of the surgical guide in BES, whereas there is only mesial tooth support in DES. Several studies reported that the resilience,[15, 51] thickness,[51, 52] or swelling of the mucosa due to local anesthesia[53] may indicate that tilting could occur when a surgical guide is supported by a soft tissue rather than being distally supported by a tooth. As larger deviations could be expected in the DES due to tilting and bending of the surgical guides, a rigid template material or the relining of the templates should be developed to obtain sufficient stiffness.[35]

We also analyzed different guided surgical protocols. The surgical guide can be used in three different steps in implant placement surgery. In the fully guided surgical protocol, the surgical guide is used from the first drilling of osteotomies to implant placement. In contrast, in the partially guided surgical protocol, the surgical guide is used only at the osteotomies steps, and consequent implant placement is conducted without the surgical guides. In another protocol, the surgical guide is only used at the pilot/first drilling of the osteotomy.[25] Our meta-analysis compared only pilot-drilling and fully guided surgery protocols because a partially guided surgery protocol was not reported in one of the two included studies.[26] An important finding of our meta-analysis was the significantly better accuracy in all parameters when performing fully guided than pilot-drill guided surgical protocols. Moreover, other studies also demonstrated the superiority of the fully guided surgical protocol.[25, 35, 54] It is clear that manual osteotomies and/or implant placement in pilot-drill and partially guided surgery could lead to higher deviation. Two RCTs described that the static guided approach significantly improved the accuracy of implant placement compared to freehand surgery.[25, 26] Nevertheless, there are several cases where the surgical guides can only be used for osteotomies due to mouth opening limitations or restricted inter-arch clearance.[7] Further, the fully guided surgical protocol demands a higher operational cost. Thus, the partially guided protocol is still acceptable and clinically justified.[55]

The surgical flap approach types were also analyzed in three studies.[33, 35, 38] However, meta-analysis could not be performed because the outcome data were insufficient. Most studies concluded that there were no significant differences in the implant placement accuracy between the flapless and open-flap approaches. One study reported that only a significant difference in platform deviation was found, which resulted in slightly higher values for the flapless approach.[35] With computer-guided surgery, avoidance of flap elevation can lead to more precise and predictable procedures. Further, the flapless approach can reduce the patient's discomfort, surgical time, postoperative bleeding, and healing period.[56] However, flapless guided surgery should only be applied when sufficient keratinized tissue and bone volume are available. Surgical modifications, such as punch repositioning or limited flap technique, may be favored in patients with a narrow zone of keratinized mucosa and limited soft tissue volume or mesial-distal space.[57]

Two different radiographic and non-radiographic methods can be used to assess the accuracy of implant placement. The radiographic method has been generally used to evaluate the implant placement accuracy in relevant studies by matching and comparing pre- and post-operative CT images using a specific software. Recently, many studies introduced non-radiographic methods as alternative options. As all studies were performed in partially edentulous patients, it is possible to use digital data obtained from post-operative cast model scanning or IOS data to determine the placed implant position. The methods for determining the placed implant position and quantifying differences between the planned and placed positions were well described in the review by Pyo et al.[58]. In our review, four studies compared the implant placement accuracy assessment between radiological and non-radiological methods. Three studies reported that no significant difference was found between radiographic method compared with the scanned post-operative model[39] or IOS[32, 34]. In contrast, one study reported that a significantly lower deviation was found in the accuracy evaluation using model analysis than using radiographic methods. They explained that the absence of reference marker in CBCT analysis could result in higher errors during overlapping pre- and post-operative CBCT.[31] Pyo et al. recommended evaluating the accuracy using cross-validation with radiographic and non-radiographic methods to obtain more conclusive results.[58]

The included article numbers were limited to all evaluated factors, which is a limitation of our meta-analysis. Regardless of the different study designs, only two or three studies were found for each evaluated factor on implant placement accuracy. Moreover, most of the observational studies showed a medium-level risk of bias. Therefore, more RCTs and studies with a high evidence level are still required to confirm our results. Significant heterogeneity, from medium to high level, was also observed among the included studies on some evaluated factors. This heterogeneity is derived from many variations in the included studies, such as study design, methodology, technical workflow, and clinical procedures. These limitations should be considered when interpreting the results of this review.

5. Conclusion

This systematic review concluded that the type of edentulous spaces (BES or DES), surgical guide manufacturing procedures (conventional or CAD/CAM method), and guided surgery protocol (pilot-drill or fully guided surgery) can affect the accuracy of implant placement using computer-guided surgery in partially edentulous patients. There was a better accuracy when the implants were placed in the BES than in the DES. Using the CAD/CAM surgical guide and a fully guided surgery protocol, we can also improve the accuracy of the implant. Despite the benefits of computer-guided implant surgery, the results of this review suggest that clinicians should carefully assess the edentulous spaces in which the implants will be placed. In addition, the surgical guide template and protocol are essential in partially edentulous patients to achieve optimal treatment outcomes in terms of implant placement accuracy and cost-effectiveness. As only a limited number of studies were included in this meta-analysis, further well-designed clinical studies or RCTs should be conducted to confirm these findings.

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Declaration of competing interest

The authors declare that they have no competing interests.

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