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Does a fully digital workflow improve the accuracy of computer assisted implant surgery in partially edentulous patients? A systematic review of clinical trials

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One sentence summary: This article presents a review of the current evidence that showed the similar accuracy between partially- and fully-digital workflow for fully-guided computer-aided implant surgery.

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ABSTRACT

Background: Accurate implant placement is essential in reducing post-treatment complications and in ensuring a successful treatment outcome.

Purpose: To compare the accuracy of fully-guided static computer-assisted implant surgery (s-CAIS) using partially- and fully-digital workflows.

Materials and Methods: Electronic and manual literature searches were performed to collect evidence concerning the accuracy of fully-guided s-CAIS procedures utilizing tooth-supported guides. Quantitative analysis was conducted to evaluate the accuracy of partially- and fully-digital workflows, and survival rates and complications were qualitatively analyzed.

Results: Thirteen studies, including 6 randomized controlled trials (RCTs) and 7 prospective clinical studies, were selected for quantitative and qualitative synthesis. A total of 669 implants in 325 patients using s-CAIS were available for review. Meta-analysis of the accuracy revealed a total mean angular deviation of 2.68° (95% CI of 2.32° to 3.03°); mean global coronal deviation of 1.03 mm (95% CI: 0.88-1.18 mm); mean global apical deviation of 1.33 mm (95% CI: 1.17-1.50 mm); and mean depth deviation of 0.59 mm (95% CI: 0.46-0.70 mm). Minimal differences were found between the two different workflows. Few complications were reported, and survival rates were between 97.8% to 100% (range of follow-up: 12 to 24 months) in the available studies.

Conclusion: Similar accuracy is obtained when implants are placed in partially edentulous patients using fully-guided s-CAIS, independently of the workflow utilized.

INTRODUCTION:

Accurate and prosthetically-driven implant placement is essential in reducing post-treatment complications and in ensuring the highest probability of a successful treatment outcome.[1] The incorporation of cone-beam computer tomography (CBCT) into implant treatment planning allows clinicians to assess the proximity to vital anatomy and bony morphology of the future implant site prior to placement.[2] Combining CBCT analysis with either images obtained from intra- or extra-oral digital scanning allows registration of the two datasets and is a prerequisite in both partially- and fully-digital workflows, where a partially-digital workflow incorporates one or more traditional laboratory steps during the implant treatment planning phase. The utilization of digital workflows involves virtual planning of both the ideal implant positioning and prosthetic design in order to direct the fabrication of surgical guides. Drill guides are used by the surgeon during the osteotomies and implant insertion with the goal of transferring the implant position from the computer into the surgical site.

The implementation of computer-guided implant planning and placement in clinical practice is a relatively recent phenomenon aimed for a more predictable and less invasive surgical procedure.[3] However, the risk for deviation remains substantial. Deviation of planned and actual implant positioning can result from transfer errors during the software-planning stage to the surgical field as well as operator error and numerous other sources. Results of systematic reviews suggest that tooth- or mucosa-supported guides in conjunction with fully-guided surgery demonstrate greater accuracy compared to bone-supported guides and partially guided-surgery.[4-6] Ozan et al. (2009) reported angular deviations of 2.91° ± 1.3°, 4.63° ± 2.6°, and 4.51° ± 2.1° from the planned position for tooth-supported, bone-supported, and mucosa-supported guided implant surgery, respectively.[7] Tooth-supported guides resulted in significantly higher accuracy during implant placement relative to bone- and mucosa-supported guides. A recent systematic review reported a significant difference in accuracy in favor of partially edentulous relative to fully edentulous cases.[8]

In vitro and *ex-vivo* studies are immune from many of the confounding clinical factors that can impair the accuracy of implant placement by causing movement of the guide or restriction of access during surgery.[9] Implant placement in models or cadavers is more accurate due to the lack of saliva, blood, and movement of the patient, as well as increased access, which facilitates the visual and spatial control of the surgeon during the osteotomy and implant insertion. In addition, the use of a single guide throughout an osteotomy has been recommended to reduce deviations. Integration of a depth-control mechanism in fully-guided surgery, can also ensure a safe osteotomy and accurate positioning of the implants. [10]

To date, many studies have investigated the clinical accuracy of guided implant surgery utilizing a partially-digital workflow.[11-13] Recently, numerous studies have evaluated the accuracy of implant placement utilizing fully-digital approaches, with the expectation that full digitalization influences the accuracy and predictability of implant placement.[14-17] Thus, the primary aim of the present systematic review was to compare the accuracy of partially- and fully-digital workflows for static computer assisted implant surgery (s-CAIS) in fully guided tooth-supported cases.

2. Materials and Methods

2.1 Study Registration

The protocol of the present article has been registered in the PROSPERO database (www.crd.york.ac.uk/PROSPERO) and allocated the identification number CRD42020165213.

2. 2 Search Strategy

The present systematic review followed the PRISMA guidelines for reporting on the accuracy of implant placement, survival, and complications for fully-guided s-CAIS in partially edentulous patients in order to compare partially- and fully-digital workflows. The term "partially edentulous patient" was used to define any patient that was missing one or more teeth, but not all teeth. A partially-digital workflow was defined as the inclusion of at least one laboratory step when obtaining

data before digital implant planning and guide design. A fully-digital workflow was considered a sequence of procedures using only virtual imaging and designing for implant surgical planning and guide fabrication. The following PICO question[18] was formulated to address the specific aim of the study: "What is the accuracy of fully-guided s-CAIS using partially or fully-digital workflows in partially edentulous human subjects?"

- Population (P): partially edentulous patients,
- Intervention (I): fully-digital workflow for tooth-supported fully-guided s-CAIS,
- Comparison (C): partially-digital workflow for tooth-supported fully-guided s-CAIS,
- Outcomes (O): accuracy of implant positioning and subsequent survival rates and complications,
- Study design (S): randomized clinical trials (RCTs), prospective clinical studies, and case series with a minimum of 10 patients.

Electronic searches were performed in three databases—Pubmed/MEDLINE, EMBASE and Cochrane Central for articles written in English published up to January 31, 2020. The search terms comprising the combination of key words were: (((((((((dental implant[MeSH Terms]) OR dental implantation[MeSH Terms]) OR dental implants[Title/Abstract]) OR implants[Title/Abstract])) AND ((((computer assisted surgery[MeSH Terms]) OR computer aided surgery[MeSH Terms]) OR computer guided[Title/Abstract]) OR guided surgery[Title/Abstract])))) AND ((accuracy[Title/Abstract]) OR deviation[Title/Abstract]).

In addition, a manual search of related articles was performed in the following relevant journals: *Clinical Implant Dentistry and Related Research*, *Clinical Oral Implants Research*, *The International Journal of Oral Maxillofacial Surgery*, *International Journal of Oral Implantology*, *Journal of Periodontology*, *Journal of Periodontal Research*, *Journal of Clinical Periodontology*, *Journal of Prosthetic Dentistry*, *Implant Dentistry*, *The International Journal of Oral and Maxillofacial Implants*, and *The International Journal of Periodontics and Restorative Dentistry*. In addition, the reference lists

of the subsequently selected abstracts and the bibliographies of the systematic reviews were searched manually.

2.3 Study Selection

Two reviewers (R.S. and Z.C.) screened all titles and abstracts independently. Full-text evaluation of the remaining publications was performed using the inclusion and exclusion criteria listed below.

Inclusion criteria:

(1) Randomized or nonrandomized prospective clinical studies, or case series when a minimum of 10 patients underwent surgical intervention;
(2) CT or CBCT scan was used for computerized planning prior to the design of a surgical guide;
(3) Intraoral scanning (IOS), tomographic templates, or extra-oral scanning of patient casts were used for data acquisition;
(4) Both implant site preparation and implant insertion were performed using tooth-supported s-CAIS;
(5) Deviations between planned and final implant positions were measured digitally.

Exclusion criteria:

(1) *In vitro* or *ex vivo* studies, reviews, or expert opinions;
(2) Implant surgery via partially-guided approaches, as defined before;
(3) Studies with fully edentulous patients, as well as zygomatic, pterygoid, and/or orthodontic implants;
(4) Studies reporting on dynamic computer-navigated surgery and 2D radiographic-based stents;

2.4 Data extraction and Statistical Analysis

Two reviewers, R.S. and Z.C., independently extracted data from the included studies. Disagreements were resolved through discussion with a third author (M.G.) for reaching a consensus. Where data was unclear or incomplete, the authors of the publication were contacted for further explanation. Data such as implant deviations, workflow utilized, implant survival, and complications were collected and systematically analyzed until a consensus was reached between both reviewers. The data was quantitatively analyzed for accuracy of implant position and qualitatively assessed for survival rates and complications.

All statistical analyses were conducted using a statistical software program (Stata software, v14.0, StataCorp, College Station, TX). The cumulative deviations in implant positioning, including global deviation at the level of the shoulder and apex, angular deviation, and depth deviation were calculated with 95% CIs using a random effects model to avoid potential bias from methodologic differences amongst included studies (Fig. 1). Subgroup analyses was performed to compare partially and fully-digital workflow groups.

2.5 Quality assessment

The risk of bias in the included RCTs was evaluated using the Cochrane collaboration tool.[19] Seven criteria were assessed: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and any other potential biases. Depending on the descriptions given for each individual criterion, a rating of low, unclear, or high risk of bias was assigned. Meanwhile, the Newcastle–Ottawa Scale (NOS) was used to evaluate the included non-randomized clinical trials.[20] Each included study could receive a maximum of nine stars to indicate methodological quality and risk of bias. Studies with 7–9 points were arbitrarily considered to have had a low risk of bias, with 4–6 points indicating a moderate risk of bias, and fewer than four points indicating a high risk of bias.

3 RESULTS

3.1 Study Selection

The initial electronic search through Pubmed/MEDLINE, EMBASE, and Cochrane Central for articles yielded 882 articles. An additional four articles were identified with manual searches yielding a total of 886 articles for review. After removing duplicates, 717 papers were available for screening. After exclusion based on title, abstracts of 139 papers were evaluated, and 41 articles were selected for independent full-text reviews by two investigators (R.S, Z.C). After screening the remaining studies based on the inclusion and exclusion criteria as well as the PICOS question, 28 articles were excluded (Supplemental Table 1), and 13 studies were ultimately selected for quantitative and qualitative synthesis (Fig. 2). From these 13 studies, six were randomized controlled trials (RCTs), and seven were prospective clinical studies. Table 1 details the articles selected for inclusion. Kappa scores were calculated, yielding 0.87 in title/abstract screening and 0.92 in full text evaluation. Any disagreement was solved by a discussion.

3.2 Study characteristics

The 13 studies included in this review assessed the outcomes of fully-guided s-CAIS surgery in partially edentulous patients. All implants in all studies were virtually planned with the use of a software program and information from CBCT scans. Only data from tooth-supported guides was analyzed whereas data on other support mechanisms were excluded. Partially-digital workflow data on accuracy was extracted from 9 studies. Among the 9 studies, 3 studies[21-23] utilized laboratory-based surgical templates with a dual-scan protocol as a reference for implant planning and surgical guides design, 3 studies[10, 12, 24] digitized stone casts with extra-oral optical scanners to make 3D digital models for implant planning, and 1 study[25] utilized the CBCT scan of a conventional polyvinyl siloxane (PVS) impression to obtain the 3D model for implant planning. The remaining 2 studies directly compared a partially-digital workflow utilizing digitized stone casts with extra-oral optical scanners versus a fully-digital workflow with models obtained via IOS.[14, 26] Data for the fully-digital workflow group were extracted from the two previously mentioned RCTs[14, 26] which included

information on both partially- and fully-digital workflows, and 4 additional studies which reported solely on fully-digital workflow.[15-17, 27]

3.3 Results of the individual studies

A total of 13 studies met the selection criteria for review (Fig 2). This provided 669 implants in 325 patients. A total of 9 different software systems were used for pretreatment planning of the cases: (a) coDiagnostix (3/13) (b) 3Diagnosys (2/13) (c) R2Gate (2/13) (d) Simplant (2/13) (e) Implant Studio (1/13) (f) Dental Slice (1/13) (g) Smart Guide (1/13) (h) Implant Master (1/13) (Table 1). 3Diagnosys and Implant studio were both utilized in one study.[27]

Regarding implant surgery, 6 out of 13 studies reported on flapless surgical implant placement, 3 out of 14 studies reported an open flap approach solely, and the remaining 4 studies completed surgery with both flapless and open-flap techniques. Regarding the comparison of the planned and final implant positions, 9 studies took CBCT before and after the surgery, while 4 studies utilized the superimposition of information from the preoperative CBCT with the STL (Standard Tessellation Language) file obtained by postoperative IOS.

3.4 Quality of the studies

The risk of bias in the six included RCTs was assessed and summarized in Table 2. One study[25] presented a high risk of nonrandom sequence generation, and one[26] was associated with an unclear risk. For allocation concealment, 3 studies[23, 25, 26] were found to have a high risk of bias, and one study[15] had an unclear risk. As for blinding of participants and personnel during outcome assessment, all included studies exhibited a low risk of bias. Additionally, 3 studies[14, 15, 24] were found to be of high risk during the assessment. According to incomplete outcome data and selective reporting, 3 (50%) articles showed a low risk of bias, respectively. Among all the included prospective clinical studies, there was one article[16] attained eight stars and 4 articles[17, 21, 22, 27] received seven stars, suggesting a high standard of quality. The remaining 2 articles[10, 12] only obtained 4-6 stars, representing moderate quality evidence (Table 3).

3.5 Accuracy outcomes

3.5.1 Global deviation

Regarding global deviation at both the coronal and apical portion of the implant, valid data were provided in 10 out of 13 studies, including 5 RCTs[15, 23-26] and 5 prospective clinical studies[12, 16, 17, 21, 22]. Among these studies, 3 articles[15-17] included a fully digital group, 6 articles[12, 21-25] included a partially-digital group, and one article[26] had both arms.

At the level of the implant shoulder, the overall weighted mean global deviation was 1.03 mm (95% CI: 0.88-1.18 mm; Figure 3). For the fully-digital group, the weighted mean deviation (coronal) was 0.89 mm (95% CI: 0.74-1.05 mm), while for the partially-digital group, this value was 1.14 mm (95% CI: 0.89-1.39 mm). At the level of the implant apex (Figure 4), the weighted mean global deviation was 1.33 mm (95% CI: 1.17-1.50 mm). In the fully-digital group, this value was 1.20 mm (95% CI: 1.02-1.39 mm) versus 1.42 mm (95% CI: 1.16-1.69 mm) for the partially-digital group.

3.5.2 Angular deviation

Angular deviation was reported in 12 out of 13 studies, including 6 RCTs[14, 15, 23-26] and 6 prospective clinical studies[12, 16, 17, 21, 22, 27]. The overall weighted mean angular deviation was 2.68°, with a 95% CI of 2.32° to 3.03° (Figure 5). For the fully-digital group[14-17, 26, 27] the mean angular deviation was 2.59° (95% CI: 1.97-3.20°), while the partially-digital group[12, 14, 21-26] showed 2.76° (95% CI: 2.30-3.23°) of angular deviation.

3.5.3 Depth deviation

Six studies[10, 12, 14, 15, 26, 27] provided depth deviation, including 3 studies[14, 15, 27] using a fully-digital approach, 2 studies[10, 12] with partially-digital approaches, and one study[26] reporting on both modalities. The weighted mean depth deviation for all the available articles was 0.59 mm (95% CI: 0.46-0.70 mm). For the fully-digital group this value was 0.55 mm (95% CI: 0.42-0.68 mm), and for the partially-digital group it was 0.62mm (95% CI: 0.38-0.87 mm; Figure 6).

3.6 Survival rates

An overall survival rate of 97.48-100% over a range of 12 to 24 months follow-up was reported from both groups, which is in line with previously reported outcomes regarding dental implant treatment. In the fully-digital group, 2 papers[16, 27] reported survival rates of 99.3% after a two-year follow-up and of 97.48% after 12.4±7.1 months follow-up, respectively. In the partially-digital group, 2 articles [12, 21] reported implant survival rates. One study[21] reported three early failures, and one study reported 100% survival during a one year follow-up[12]. One study reporting on both modalities also showed 100% survival after one year[14].

3.7 Complications

Regarding intra- and post-operative complications, no nerve injuries, abnormal hemorrhages, sinus pathologies, or other complications relating to anatomical structures were reported in either group. In the fully-digital group, 2 studies[14, 16] reported that in one case in the posterior region, the use of a surgical guide was abandoned due to limited mouth opening. In Derksen's study, they reported that 9 implants placed with a flapless approach had less than 2 mm of keratinized mucosa (KM), with 3 implants demonstrating a complete lack of KM on the buccal aspect after prosthetic reconstruction. Two sites presented with buccal dehiscence after the final drill, and simultaneous bone augmentation procedures were performed with implant placement. In the partially-digital group, two articles[22, 23] reported complications. Farley and coworkers reported guide instability that required an acrylic resin reline. Magrin et al. 2020 reported one case with a buccal bone fracture which occurred during implant insertion, and one case with fracture of the insertion driver.

4. DISCUSSION

The present systematic review evaluated the literature concerning the accuracy of s-CAIS utilizing partially- and fully-digital workflows. Previous studies reporting on the accuracy of s-CAIS suggested that fully-guided tooth-supported systems exhibited less deviations compared to other

types of support mechanisms and partially-guided protocols[8, 16]. The current review focused only on implants placed in human subjects, with the main inclusion criteria being partially edentulous patients that received implant placement through a fully-guided protocol using tooth-supported guides.

To the best of our knowledge, this is the first systematic review comparing the accuracy of partially- and fully-digital workflows, which yielded similar mean angular deviations of 2.76° (95% CI: 2.30-3.23°) and 2.59° (95% CI: 1.97-3.20°), respectively. The overall mean angular deviation for both groups encountered in the present study of 2.68° (95% CI: 2.32-3.03°) was slightly lower compared to the results of clinical studies included in previous systematic reviews[8, 28, 29]. Tahmaseb et al. (2014) reported an average angular deviation of 3.53° for fully-guided implant placement. However, there was heterogeneity in the mechanisms of guide support amongst the included studies, which could have contributed towards a greater deviation. Bover-Ramos et al. (2018) reported a higher mean angular deviation of 3.62 ± 0.29° for the included clinical studies for fully-guided implant surgery, but the majority of included studies utilized mucosa- and bone-supported guides. In a more recent systematic review, Tahmaseb et al. (2018) reported a mean angular deviation of 3.3°(95% CI: 2.07-4.63°) for fully-guided tooth-supported implant surgery, however, only 2 studies with retrospective designs using partially-digital workflows were included. Another possible explanation for the lower deviations encountered in our review is the inclusion of a study that used templates without metallic sleeves and a stopless implant driver that contributed to less angular and horizontal deviation.[27] Additionally, the evolution of 3D printing technologies may contribute to more accurate surgical templates in the recently published included studies. Despite the observation that the utilization of a fully-digital workflow resulted in a slightly smaller angular error, this difference cannot be considered of clinical relevance. Similar conclusions were drawn in 2 different RCTs[14, 26]. The authors conducted s-CAIS with stereolithographic guides manufactured in conjunction with either intra- or extra-oral scans and reported equal accuracy of implant positioning between the two workflows. It is worth noting that the highest mean angular deviation observed among the included studies in this review was 3.85° ± 1.83°[17], which was substantially lower

compared to earlier reports on guided surgery using both tooth- and bone-supported guides where a mean angle up to 7.25 ± 2.67° was observed.[30]

For tooth-supported guides, higher deviations can be expected for cases with reduced dentition, as fewer teeth are present to support the guide. Kholy et al. (2019) conducted an *in vitro* study and reported that guides supported by a minimum of four teeth (two teeth on each side of an edentulous span) resulted in similar accuracy outcomes to full-arch-supported guides. Guides supported only by anterior teeth and distal extension scenarios were associated with significantly greater deviations. The present review included studies with heterogeneity regarding the number of single tooth gaps, distal extensions, and teeth available to support the guide. Because of variations in the number of existing teeth, it was difficult to make comparisons between the results of these studies. However, the majority of included studies acknowledged the importance of at least five teeth in two quadrants for supporting the surgical template for cross-arch stabilization.

The utilization of a fully-guided workflow has been demonstrated to increase the accuracy of implant placement relative to partially-guided surgery, where the template is removed after osteotomy preparation but prior to implant placement.[29, 31] Although the present review focused only on evaluating the accuracy of fully-guided surgical procedures, two of the included studies[14, 16] reported as a complication that the surgical guide had to be abandoned intra-operatively due to limited mouth opening during implant placement in the posterior region. Although not observed in this study, limited inter-arch clearance and mesiodistal spacing in single-tooth gaps may limit the use of surgical guides during osteotomy preparation. The present review reported a mean global deviation of 1.03 mm (95% CI: 0.88-1.18 mm) at the shoulder and 1.33 mm (95% CI: 1.17-1.50 mm) at the apex, which was similar between groups. Tahmaseb et al. (2018) reported similar mean errors of 0.9 mm (95% CI: 0.79-1.00 mm) at the entry point and 1.2 mm (95% CI: 1.11-1.20 mm) at the apex for partially edentulous cases. The magnitude of the upper limit of the confidence interval for the deviations from the studies should be considered in treatment planning and included as a safety margin.

Guided implant surgery facilitates a minimally invasive approach with conservative flap elevation or even flapless implant surgery.[32] This current review suggested both workflows can

successfully incorporate the flapless approach. However, Derksen et al. (2019) found that 9 out of 34 implants placed using a flapless approach resulted in an inadequate zone of KM < 2 mm, with 3 implants completely lacking KM at the buccal aspect following prosthetic rehabilitation. Proper case selection and thorough treatment planning are key to avoid these potential complications.

Depth control can be achieved via indication lines or physical stoppers on the drills to aid with osteotomy preparation, guided surgical mounts with indication lines or physical stoppers to facilitate implant placement, as well as metal sleeves of varying diameters inserted in the guide.[15, 16, 33] During analysis of depth deviation, most included studies reported absolute values, while one study[14] took direction into consideration with positive (apical to the plan) and negative (coronal to the plan) values. This study utilizes absolute values, since the use of positive and negative values during deviation analysis may result in lower deviation outcomes than actually experienced. A weighted depth deviation of 0.59 mm (95% CI: 0.46-0.70 mm) was found in the present review. For the fully-digital workflow group, this value was 0.55 mm (95% CI: 0.42-0.68 mm), compared to 0.62 mm (95% CI: 0.38-0.87 mm) in the partially-digital group. Ultimately, it is meaningful to consider depth deviation in the apico-coronal dimension in the context of long-term outcomes such as bone remodeling and pocket formation, whereas errors in implant height at the apex are more directly related to proximity to vital anatomical structures. As a result, we suggest studies report both absolute value and considering direction in the future.

Placement deviation is cumulative errors during all phases of s-CAIS protocols. CBCT acquisition errors include patient movement[34] and imaging artifacts.[35] It was speculated that the application of a fully-digital workflow, in contrast to earlier methods combining digital and laboratory steps, could have an influence on the accuracy of s-CAIS.[16] In the present review, deviations in the accuracy of implant placement were slightly lower for fully-digital approaches compared to the partially-digital group, but a clinically significant difference was not found. This is likely due to the fact that investigators in the partially-digital group utilized mostly stable elastomeric impression materials (polyvinylsiloxane and polyether) and followed a strict protocol adhering to manufacturer recommendations when obtaining impressions and fabricating stone casts. Also, desktop scanners can digitize stone casts or conventional impressions with high

accuracy.[36] A recent investigation by Marghalani et al[37] demonstrated that the use of a specific IOS system obtained a higher level of accuracy relative to conventional impressions with polyether material, however both resulted in clinically acceptable outcomes. On the other hand, it is logical to assume that inaccurate impressions taken with materials such as alginate with a greater propensity for deformation may lead to errors that will ultimately be incorporated into the guide and surgery. It is also possible to consider that errors could be introduced during the disinfection of the impression and pouring of the casts if adequate protocols are not followed.

A limitation of the present review involves the heterogeneity among the workflows of the included studies, including variability in the type of implant system used, the number of remaining teeth supporting the surgical template, as well as patient anatomical considerations, which made comparisons difficult between studies. Additionally, in patient-oriented dental implant research, clustered or dependent observations resulting from multiple implants placed in the same patient can potentially have a large influence on outcomes and is a common problem in this field.

The strengths of this review are as follows. The authors are unaware of a previous systematic review comparing the accuracy of implant placement between partially- and fully-digital workflows. The presence of strict inclusion criteria is an additional asset as this limited the influence of confounding variables such as different support mechanisms seen in other studies. In addition, only clinical studies were included, which increases the translatability of the results to clinical practice.

Clinical implications

The differences found in this review were of a magnitude that would not likely jeopardize the aesthetic outcome, the safety of surrounding anatomical structures, nor the final prosthetic treatment plan from being executed as planned. However, these results should be interpreted with caution, and the maximum deviation should be taken into account as a safety margin since the involuntary contact of the implant with any critical anatomical structure can cause serious complications. Although no difference was found between partially- and fully-digital workflows, a fully-digital workflow with IOS can aid in reducing working time and improving the patient experience.[38]

Research implications

Tahmaseb et al. (2018) recognized that the method used for obtaining the postoperative implant position could affect imaging quality. However, there was insufficient data available within their systematic review to be able to evaluate the effects of this on the outcome of guided surgery.[8] In our study, 10 publications used superimposition of virtually planned position and post-CBCT data, while 4 studies evaluated accuracy by obtaining post-surgical data using IOS. The differences between studies using the two methods were negligible, and comparable results were also demonstrated in a recent clinical trial comparing the two methods directly.[39] Still, few studies specifically addressed whether guided surgery can improve the likelihood of obtaining the desired prosthetic and aesthetic outcomes. In addition, another variable that remains to be further explored is whether long-term peri-implant survival and success are affected by optimal implant positioning. Although there is a current trend towards the utilization of fully-digital workflows, future research should focus on long-term follow-ups to provide further insight into the potential benefits of this approach.

Conclusion

Within the limitations of the present systematic review, similar accuracy is obtained when implants are placed in partially edentulous patients using fully-guided s-CAIS independent of the workflow utilized for implant planning and surgical guide fabrication. Therefore, the decision to utilize either a partially- or fully-digital workflow for partially edentulous patients should take into account operator preference, cost, and patient comfort.

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References

1. Papaspyridakos P, Barizan Bordin T, Kim YJ, et al. Implant survival rates and biologic complications with implant-supported fixed complete dental prostheses: A retrospective study with up to 12-year follow-up. *Clin Oral Implants Res* 2018;29:881-893.
2. Chan HL, Wang HL. Sinus pathology and anatomy in relation to complications in lateral window sinus augmentation. *Implant Dent* 2011;20:406-412.
3. D'Haese J, Ackhurst J, Wismeijer D, De Bruyn H, Tahmaseb A. Current state of the art of computer-guided implant surgery. *Periodontol* 2017;73:121-133. doi: 110.1111/prd.12175.
4. Van Assche N, Vercruyssen M, Coucke W, Teughels W, Jacobs R, Quirynen M. Accuracy of computer-aided implant placement. *Clin Oral Implants Res* 2012;23:112-123. doi: 110.1111/j.1600-0501.2012.02552.x.
5. Raico Gallardo YN, da Silva-Olivio IRT, Mukai E, Morimoto S, Sesma N, Cordaro L. Accuracy comparison of guided surgery for dental implants according to the tissue of support: a systematic review and meta-analysis. *Clin Oral Implants Res* 2017;28:602-612. doi: 610.1111/clr.12841. Epub 12016 Apr 12848.
6. Zhou W, Liu Z, Song L, Kuo CL, Shafer DM. Clinical Factors Affecting the Accuracy of Guided Implant Surgery-A Systematic Review and Meta-analysis. *J Evid Based Dent Pract* 2018;18:28-40. doi: 10.1016/j.jebdp.2017.1007.1007. Epub 2017 Jul 1022.
7. Ozan O, Turkyilmaz I, Ersoy AE, McGlumphy EA, Rosenstiel SF. Clinical accuracy of 3 different types of computed tomography-derived stereolithographic surgical guides in implant placement. *J Oral Maxillofac Surg* 2009;67:394-401. doi: 310.1016/j.joms.2008.1009.1033.
8. Tahmaseb A, Wu V, Wismeijer D, Coucke W, Evans C. The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clin Oral Implants Res* 2018;29:416-435. doi: 410.1111/clr.13346.
9. Jung RE, Schneider D, Ganeles J, et al. Computer technology applications in surgical implant dentistry: a systematic review. *Int J Oral Maxillofac Implants* 2009;24:92-109.
10. Lee DH, An SY, Hong MH, Jeon KB, Lee KB. Accuracy of a direct drill-guiding system with minimal tolerance of surgical instruments used for implant surgery: a prospective clinical

study. *J Adv Prosthodont* 2016;8:207-213. doi: 210.4047/jap.2016.4048.4043.4207. Epub 2016 Jun 4017.

11. Behneke A, Burwinkel M, Knierim K, Behneke N. Accuracy assessment of cone beam computed tomography-derived laboratory-based surgical templates on partially edentulous patients. *Clin Oral Implants Res* 2012;23:137-143. doi: 110.1111/j.1600-0501.2011.02176.x. Epub 02011 Mar 02128.
12. Cristache CM, Gurbanescu S. Accuracy Evaluation of a Stereolithographic Surgical Template for Dental Implant Insertion Using 3D Superimposition Protocol. *Int J Dent* 2017;2017:4292081.:10.1155/2017/4292081. Epub 4292017 May 4292087.
13. Zhao XZ, Xu WH, Tang ZH, Wu MJ, Zhu J, Chen S. Accuracy of computer-guided implant surgery by a CAD/CAM and laser scanning technique. *Chin J Dent Res* 2014;17:31-36.
14. Tallarico M, Xhanari E, Kim YJ, et al. Accuracy of computer-assisted template-based implant placement using conventional impression and scan model or intraoral digital impression: A randomised controlled trial with 1 year of follow-up. *Int J Oral Implantol (New Malden)* 2019;12:197-206.
15. Smitkarn P, Subbalekha K, Mattheos N, Pimkhaokham A. The accuracy of single-tooth implants placed using fully digital-guided surgery and freehand implant surgery. *Journal of clinical periodontology* 2019.
16. Derksen W, Wismeijer D, Flugge T, Hassan B, Tahmaseb A. The accuracy of computer guided implant surgery with tooth supported, digitally designed drill guides based on CBCT and intraoral scanning. A prospective cohort study. *Clin Oral Implants Res* 2019;22:13514.
17. Skjerven H, Riis UH, Herlofsson BB, Ellingsen JE. In Vivo Accuracy of Implant Placement Using a Full Digital Planning Modality and Stereolithographic Guides. *Int J Oral Maxillofac Implants* 2019;34:124-132. doi: 110.11607/jomi.16939.
18. Stone PW. Popping the (PICO) question in research and evidence-based practice. *Appl Nurs Res* 2002;15:197-198.
19. Higgins JP, Altman DG, Gotzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ* 2011;343:d5928.
20. Stang A. Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. *Eur J Epidemiol* 2010;25:603-605.
21. Arisan V, Karabuda ZC, Özdemir T. Accuracy of two stereolithographic guide systems for computer-aided implant placement: A computed tomography-based clinical comparative study. *Journal of Periodontology* 2010;81:43-51.
22. Farley NE, Kennedy K, McGlumphy EA, Clelland NL. Split-mouth comparison of the accuracy of computer-generated and conventional surgical guides. *Int J Oral Maxillofac Implants* 2013;28:563-572. doi: 510.11607/jomi.13025.
23. Magrin GL, Rafael SNF, Passoni BB, et al. Clinical and tomographic comparison of dental implants placed by guided virtual surgery versus conventional technique: A split-mouth randomized clinical trial. *J Clin Periodontol* 2020;47:120-128.

24. Younes F, Cosyn J, De Bruyckere T, Cleymaet R, Bouckaert E, Eghbali A. A randomized controlled study on the accuracy of free-handed, pilot-drill guided and fully guided implant surgery in partially edentulous patients. *Journal of clinical periodontology* 2018;45:721-732.
25. Varga E, Jr., Antal M, Major L, Kiscsatari R, Braunitzer G, Piffko J. Guidance means accuracy: A randomized clinical trial on freehand versus guided dental implantation. *Clin Oral Implants Res* 2020.
26. Kiatkroekkrai P, Takolpuckdee C, Subbalekha K, Mattheos N, Pimkhaokham A. Accuracy of implant position when placed using static computer-assisted implant surgical guides manufactured with two different optical scanning techniques: a randomized clinical trial. *Int J Oral Maxillofac Surg* 2020;49:377-383.
27. Tallarico M, Kim YJ, Cocchi F, Martinolli M, Meloni SM. Accuracy of newly developed sleeve-designed templates for insertion of dental implants: A prospective multicenters clinical trial. *Clinical implant dentistry and related research* 2019;21:108-113.
28. Tahmaseb A, Wismeijer D, Coucke W, Derksen W. Computer technology applications in surgical implant dentistry: a systematic review. *Int J Oral Maxillofac Implants* 2014;29 Suppl:25-42.
29. Bover-Ramos F, Vina-Almunia J, Cervera-Ballester J, Penarrocha-Diago M, Garcia-Mira B. Accuracy of Implant Placement with Computer-Guided Surgery: A Systematic Review and Meta-Analysis Comparing Cadaver, Clinical, and In Vitro Studies. *Int J Oral Maxillofac Implants* 2018;33:101-115. doi: 110.11607/jomi.15556. Epub 12017 Jun 11620.
30. Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol* 2005;76:503-507.
31. Pozzi A, Polizzi G, Moy PK. Guided surgery with tooth-supported templates for single missing teeth: A critical review. *Eur J Oral Implantol* 2016;9:S135-153.
32. Colombo M, Mangano C, Mijiritsky E, Krebs M, Hauschild U, Fortin T. Clinical applications and effectiveness of guided implant surgery: a critical review based on randomized controlled trials. *BMC Oral Health* 2017;17:150. doi: 110.1186/s12903-12017-10441-y.
33. Vercruyssen M, Coucke W, Naert I, Jacobs R, Teughels W, Quirynen M. Depth and lateral deviations in guided implant surgery: an RCT comparing guided surgery with mental navigation or the use of a pilot-drill template. *Clin Oral Implants Res* 2015;26:1315-1320. doi: 1310.1111/clr.12460. Epub 12014 Sep 12462.
34. Pettersson A, Komiyama A, Hultin M, Nasstrom K, Klinge B. Accuracy of virtually planned and template guided implant surgery on edentate patients. *Clin Implant Dent Relat Res* 2012;14:527-537. doi: 510.1111/j.1708-8208.2010.00285.x. Epub 02010 May 00211.
35. Tadinada A, Jalali E, Jadhav A, Schincaglia GP, Yadav S. Artifacts in Cone Beam Computed Tomography Image Volumes: An Illustrative Depiction. *J Mass Dent Soc* 2015;64:12-15.
36. Runkel C, Guth JF, Erdelt K, Keul C. Digital impressions in dentistry-accuracy of impression digitalisation by desktop scanners. *Clin Oral Investig* 2020;24:1249-1257.

37. Marghalani A, Weber HP, Finkelman M, Kudara Y, El Rafie K, Papaspyridakos P. Digital versus conventional implant impressions for partially edentulous arches: An evaluation of accuracy. *J Prosthet Dent* 2018;119:574-579.
38. Gallardo YR, Bohner L, Tortamano P, Pigozzo MN, Lagana DC, Sesma N. Patient outcomes and procedure working time for digital versus conventional impressions: A systematic review. *J Prosthet Dent* 2018;119:214-219.
39. Skjerven H, Olsen-Bergem H, Ronold HJ, Riis UH, Ellingsen JE. Comparison of postoperative intraoral scan versus cone beam computerised tomography to measure accuracy of guided implant placement-A prospective clinical study. *Clin Oral Implants Res* 2019;30:531-541.

Figures legend

Figure 1. Diagram illustrating deviation measurements evaluated in this review.

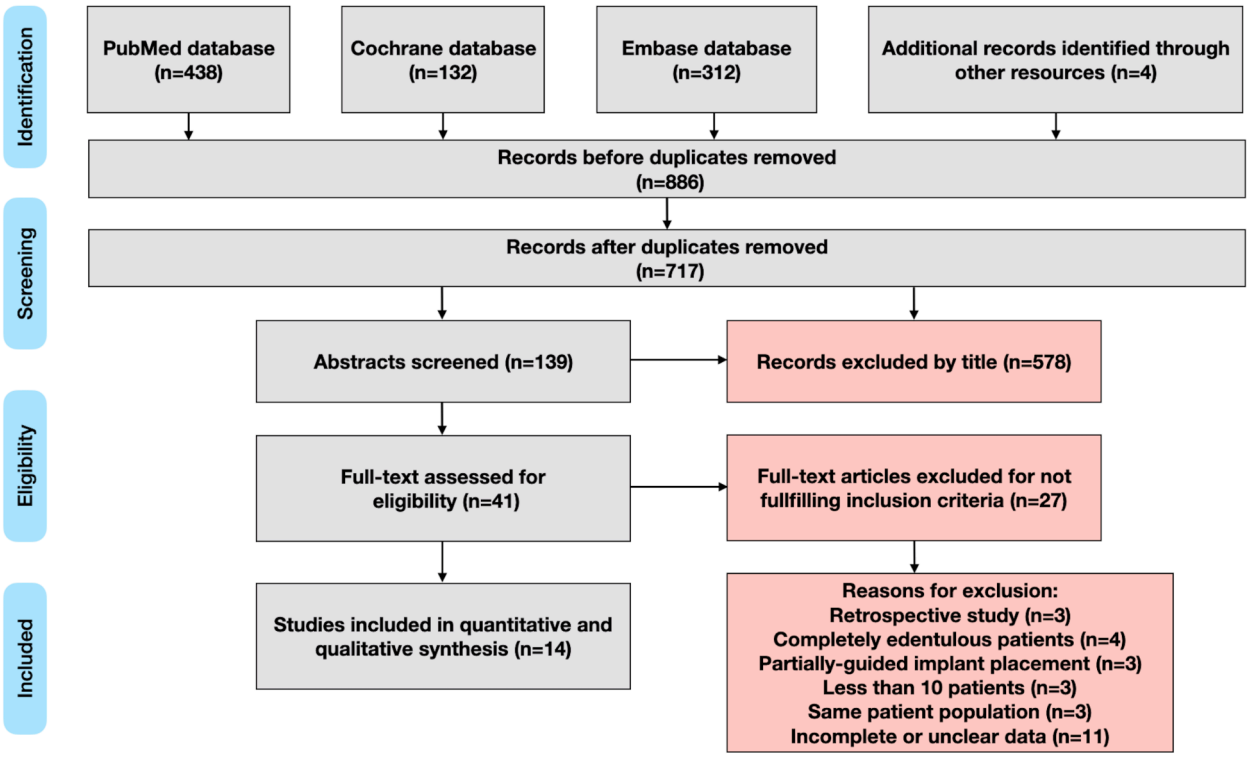
Figure 2. PRISMA flowchart of the screening process. A total of 14 articles were included for quantitative and qualitative assessment

Figure 3. Cumulative global deviations (coronal) of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval).

Figure 4. Cumulative global deviations (apex) of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval).

Figure 5. Cumulative angular deviations of partially- and fully-digital groups among selected studies (ES, effect sizes; CI, confidence interval).

Figure 6. Cumulative depth deviations of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval).



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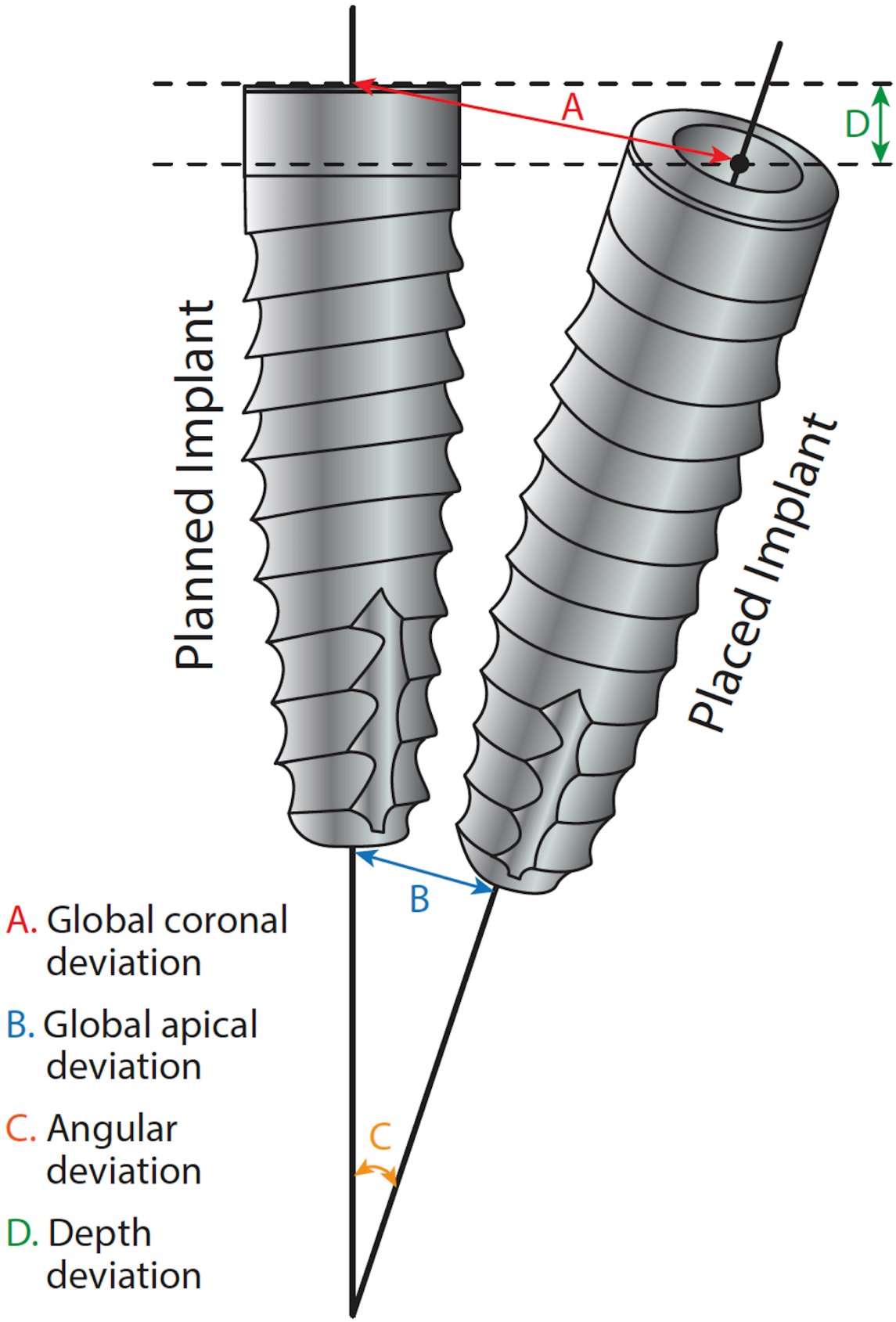
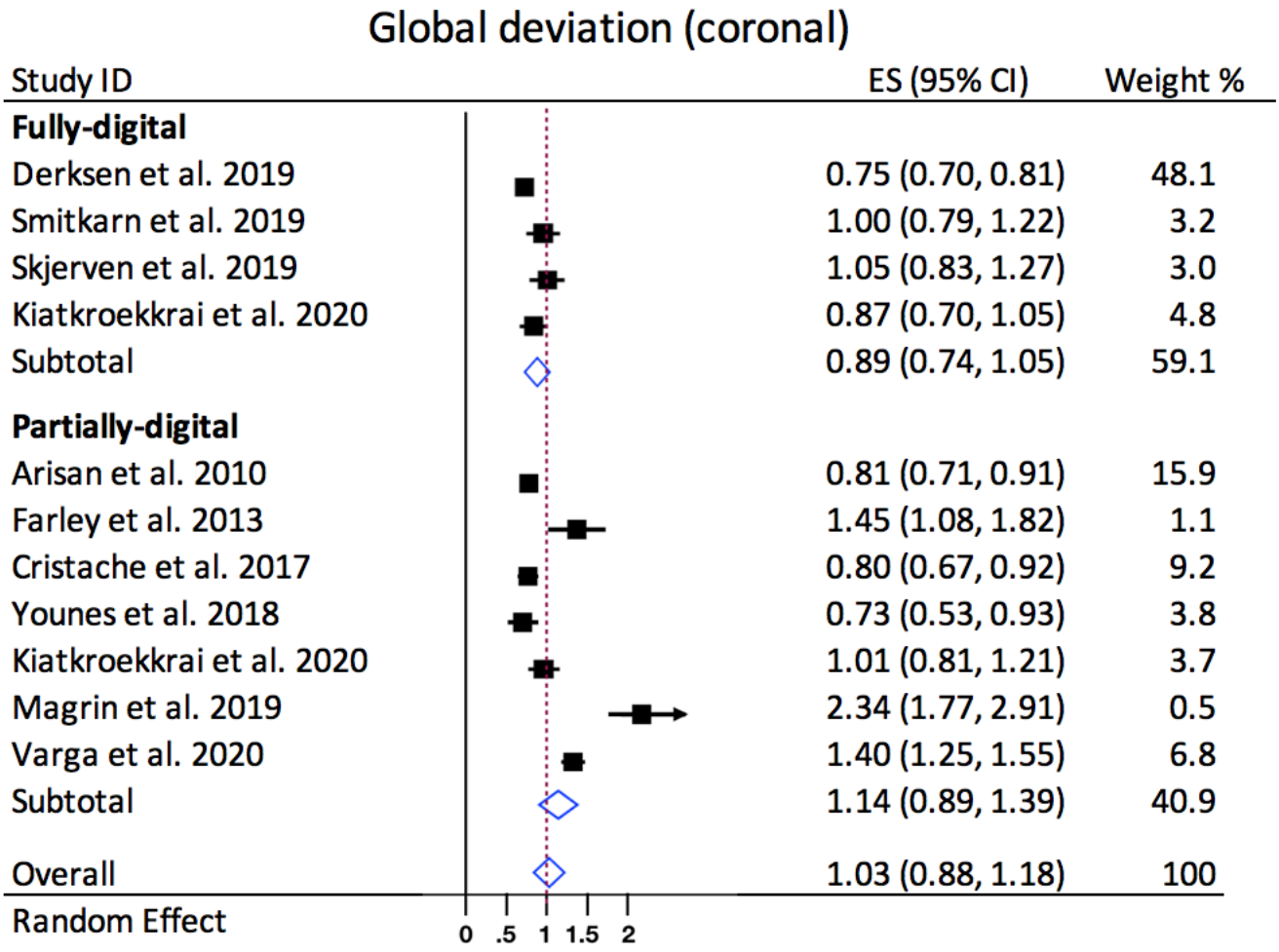


CID_12937_Fig. 1 Diagram implant planned vs placed.png



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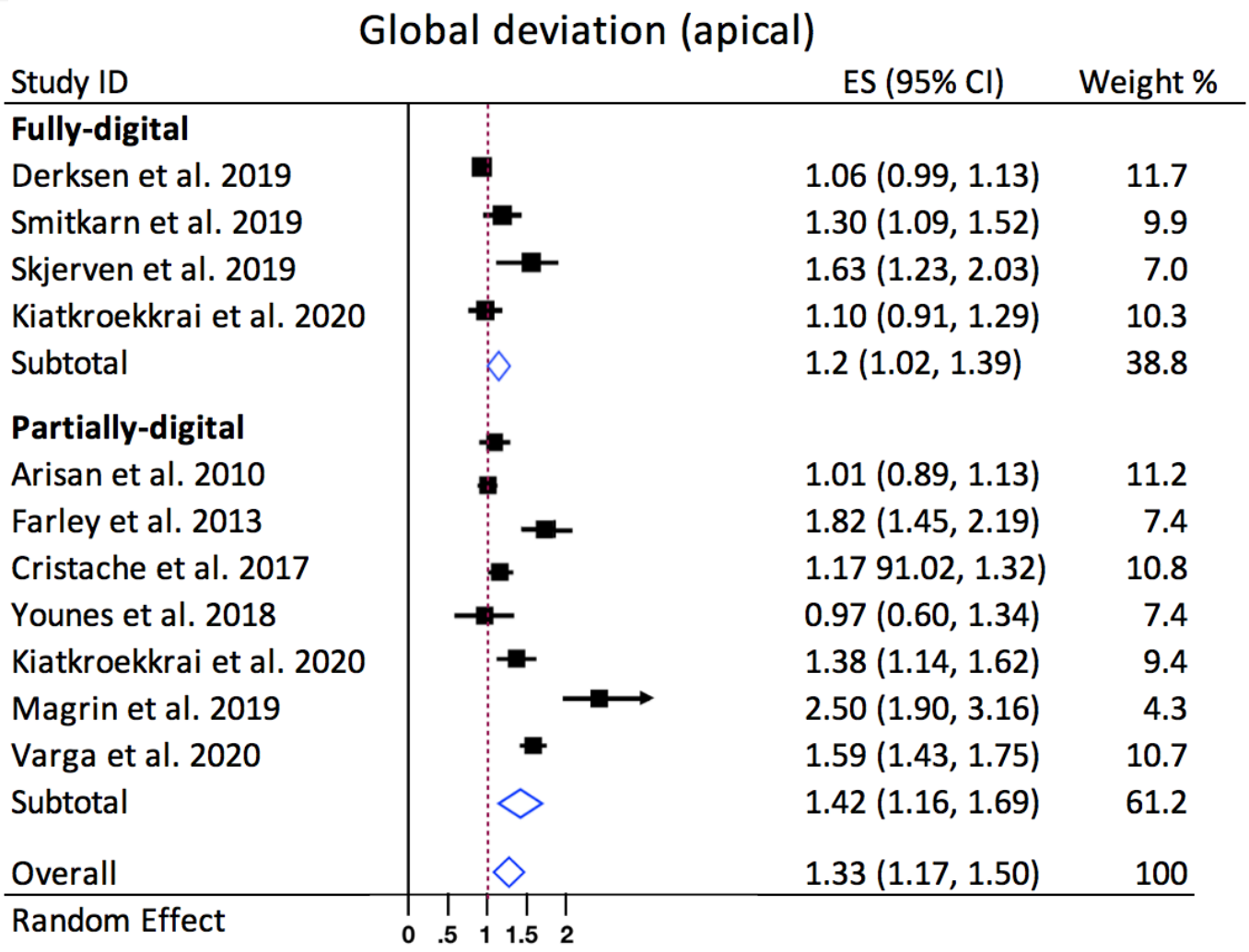

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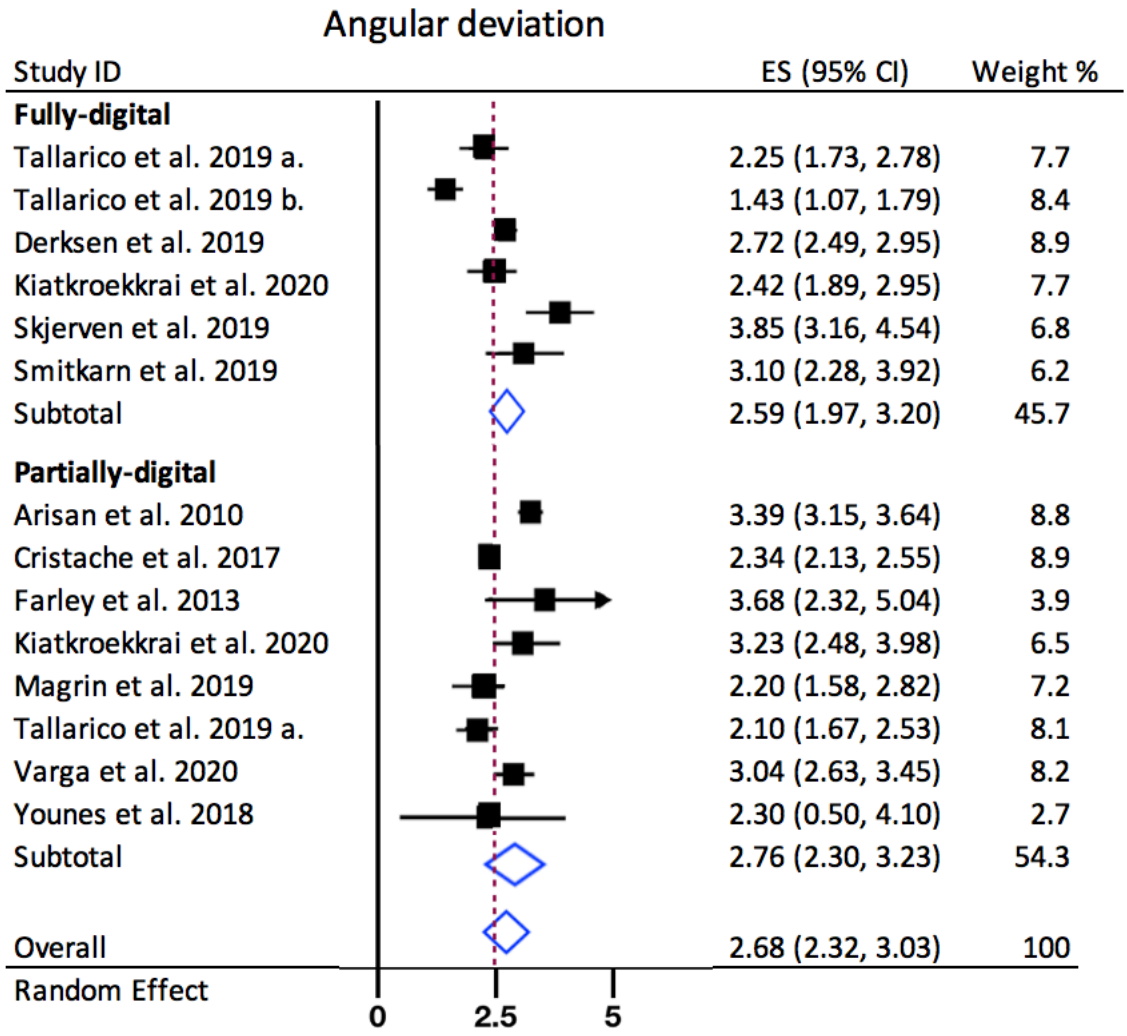

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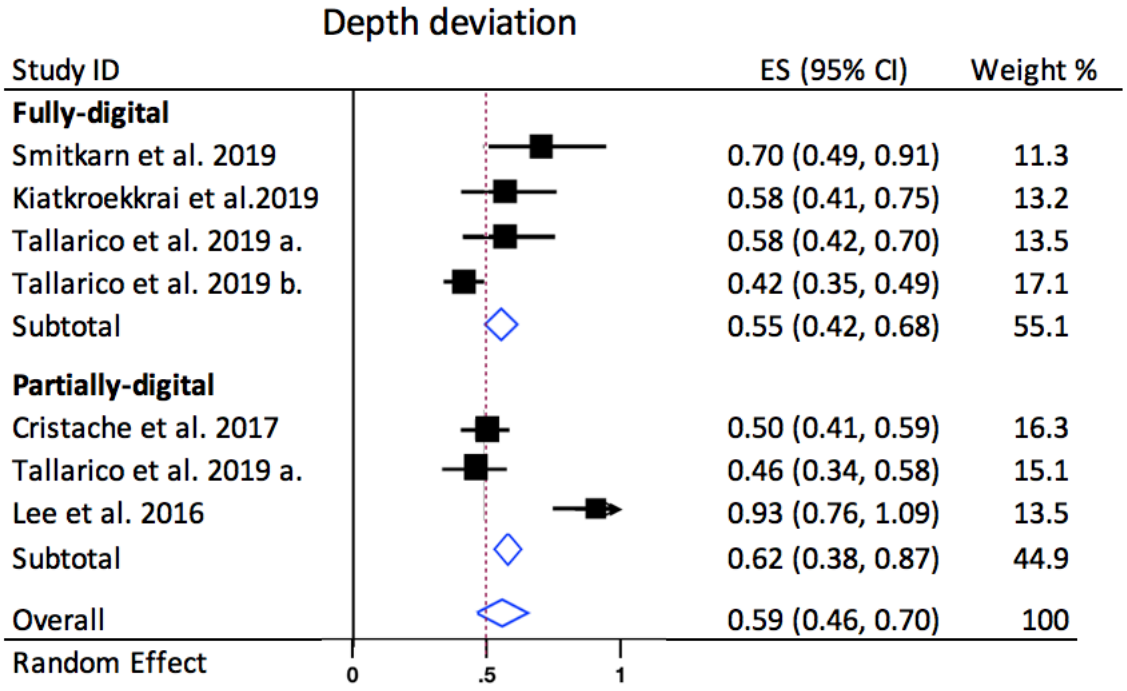

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Table 1. Publications included in the meta-analysis.

Author (year)	Study design	Workflow utilized	Accuracy Evaluation Method	Guided System Software	N of patients	N of implants	Implant Location		Open / Flapless
							Mand	Max	
Arisan et al (2010)	Prospective Clinical Study	Partially-digital: dual-scan protocol	CBCT/CBCT	SimPlant Pro (Materialise Dental, Leuven, Belgium)	11	50	n/a		Flapless
Farley et al. (2013)	Prospective Clinical Study	Partially-digital: dual-scan protocol	CBCT/CBCT	Implant Master software (iDent Imaging, Foster City, USA))	10	10	7	3	Flapless
Lee et al. (2016)	Prospective Clinical Study	Partially-digital: stone cast digitized with desktop scanner	CBCT/CBCT	R2Gate 1.0 (MegaGen Implant, Gyeongbuk, Korea)	11	21	12	9	Flapless
Cristache et al. (2017)	Prospective Clinical Study	Partially-digital: stone cast digitized with desktop scanner	CBCT/STL	R2Gate 1.0 (Megagen Implant, Gyeongbuk, Korea)	25	65	33	32	Flapless
Younes et al. (2018)	RCT	Partially-digital: stone cast digitized with desktop scanner	CBCT/CBCT	Simplant (Dentsply Sirona Implants, Hasselt, Belgium)	10	21	-	21	Flapless
Magrin et al. (2019)	RCT	Partially-digital / dual-scan protocol	CBCT/CBCT	DentalSlice (Bioparts, Brasília, Brazil)	12	12	12	-	Flapless
Tallarico et al. (2019a)	RCT	Partially-digital: stone cast digitized with desktop scanner Fully-digital: IOS	CBCT/STL	3Diagnosys (3DIEMME srl, Cantù,Italy)	20	57	24	33	Both (not specified)
Tallarico et al. (2019b)	Prospective Clinical Study	Fully-digital: IOS	CBCT/STL	3Diagnosys (3DIEMME srl, Cantù,Italy) and Implant studio (3Shape A/S, Copenhagen, Denmark)	39	119	54	65	Both (not specified)
Derksen et al. (2019)	Prospective Clinical Study	Fully-digital: IOS	CBCT/CBCT	coDiagnostiX (Dental Wings Inc)	66	145	79	66	111 / 34
Smitkarn et al. (2019)	RCT	Fully-digital: IOS	CBCT / CBCT	coDiagnostiX (Dental Wings Inc)	26	30	10	20	Open flap
Skjerven et al. (2019)	Prospective Clinical Study	Fully-digital: IOS	CBCT / STL	Implant studio (3Shape A/S, Copenhagen, Denmark)	20	27	6	21	Open flap
Kiatkroekkrai et al. (2020)	RCT (split-mouth)	Partially-digital: stone cast digitized with desktop scanner Fully-digital: IOS	CBCT/CBCT	coDiagnostiX (Dental Wings Inc)	47	60	20	40	Both (not specified)
Varga et al. (2020)	RCT	Partially-digital: dual-scan protocol (CBCT of PVS impression and patient)	CBCT / CBCT	Smart Guide (dicomLAB Dental, Szeged, Hungary)	28	52	37	15	Open flap

Legend. RCT: randomized clinical trial. IOS: intraoral scanning. CBCT: cone-beam computer tomography. STL: standard tessellation language data. N: number. Mand: mandible. Max: maxilla. n/a: data not available

Table 2. Risk of bias assessment for included RCTs according to the Cochrane guidelines

Study	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Tallarico et al. 2019a	Low	Low	Low	High	Low	Low	Low
Smitkarn et al 2019	Low	Unclear	Low	High	Low	High	Low
Younes et al. 2018	Low	Low	Low	High	Low	Low	Low
Magrin et al 2019	Low	High	Low	Low	High	High	Low
Vagra et al. 2020	High	High	Low	Low	High	Low	Low
Kiatkroekkrai et al 2020	Unclear	High	Low	Low	High	Low	Low

Table 3. Results of Newcastle-Ottawa Scale risk of bias for non-randomized clinical trials

Fully-Digital

Study	Representative of the exposed cohort	Selection of the non-exposed cohort	Ascertainment of exposure	Outcome of interest does not present at start of study	Comparability of cohorts on the basis of the design or analysis	Assessment of outcome	Sufficient follow-up for outcome to occur	Adequacy of follow-up	Total
Derksen et al 2019	★	★	★	★	★	★	★	★	8
Skjerven et al 2019	★	★	★	★	★	☆	★	★	7
Tallarico et al 2019b	★	★	★	☆	★	★	★	★	7

Partially-Digital

Arisan et al. 2010	★	★	★	★	★	★	★	☆	7
Farley et al. 2013	★	★	★	★	★	★	★	☆	7
Cristache et al. 2017	☆	★	★	★	★	☆	★	★	6
Lee et al. 2016	☆	☆	★	★	★	☆	★	☆	4

7-9 high, 4-6 moderate, and 0-3 low quality.