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Review

Accuracy of Different Systems of Guided Implant Surgery and Methods for Quantification: A Systematic Review

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Abstract: The aim of this systematic review was to assess the scientific literature on the accuracy of guided implant surgery and the methods used for its quantification. Two reviewers searched PubMed and the Cochrane Library to identify relevant articles published before 2023. Two methodological quality-assessment tools were used to assess the quality of the studies included. Inter-investigator reliability was verified using kappa statistics. Twenty-three clinical studies out of the 3299 articles initially identified met the inclusion criteria. The "radiographic matching method" and "digital registration method" were used to assess accuracy in guided surgery. The mean angular, coronal, and apical deviations of mucosa-supported guides ranged from 2.7° to 5.14°, 0.87 mm to 2.05 mm, and 1.08 mm to 2.28 mm, respectively. With bone-supported guides, these ranged from 2.49° to 5.08°, 0.71 mm to 1.60, and 0.77 mm to 1.65 mm, respectively. In tooth-supported guides, deviations were from 2.5° to 5.62°, 0.39 mm to 1.63 mm and 0.28 mm, and 1.84 mm, respectively. Regardless of the evaluation method, all systems exhibit some error. The minimum and maximum deviation ranges found between the planned and placed implants show that, although deviations occur, guided surgery is not far from accurate.

Keywords: accuracy; guided surgery; computer-aided planning; computer-assisted; dental implants; systematic review

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1. Introduction

In recent years, ongoing research and the findings of clinical trials have brought about significant advances in implant dentistry. Implantology has emerged from an era of experiment and innovation to enter an era of scientific fact so that replacing lost teeth with dental implants is now a clinically established and scientifically documented practice [1].

Many of the most important developments seen in recent years have been due to the introduction of cone-beam computed tomography (CBCT), 3-dimensional (3D) implant planning softwares, and computer-aided design and computer-assisted manufacturing (CAD-CAM) technologies [2]. CBCT partnered with CAD/CAM allows surgical planning in virtual and 3D environments, providing clinical staff with a realistic view of the patient's bone anatomy. This makes it possible to foresee the specific conditions of the surgical procedure, as well as the exact prosthetic needs of each case [3]. Scientific research has demonstrated that the use of CBCT, together with computer-assisted treatment planning and the use of surgical guides, is now firmly established as the most accurate method for placing dental implants [4,5].

According to consensus statements regarding computer-assisted implant dentistry published in 2009 [6], there are two types of guided implant surgery protocols: static and dynamic. The term "computer-navigated (dynamic) surgery" refers to the use of a navigation system that allows real-time surgical visualization, as well as intraoperative modification of the implant position. In contrast, the term "computer-guided (static) surgery" refers to the use of a static surgical template that reproduces the virtually planned implant position but does not allow for intraoperative modification.

Static-guided surgery has allowed the development of less invasive surgical techniques such as the "flapless surgical technique", which, together with guided implant placement, improves the patient's postoperative comfort and allows adequate implant placement, along with the fabrication of prosthetic structures in advance of surgical procedures [3]. Although the advantages of this technique are evident, the literature also reports that flapless implant surgery is a blind surgical technique. On the one hand, it can cause thermal damage due to limited external irrigation during surgical drilling, and on the other, it makes it impossible to manipulate soft tissue during surgery [7]. Nevertheless, copious literature supports the reliability and safety of flapless implant surgery, providing patient selection criteria are applied correctly.

The most critical step in achieving the preoperatively planned outcome is the transfer of the virtually planned implant position from the software to the patient's mouth. However, the transference of virtual planning to the operative field without any deviation remains an unrealistic goal [8]. Accuracy in implant placement with static-guided surgery depends on multiple factors, contributing to a successive accumulation of errors from planning to surgery. A clinical trial by Marei et al. [9] classifies these errors into three groups: errors during image acquisition (the manufacture of the surgical guide, the acquisition of CBCT images, CBCT surface registrations, and dental registrations), errors related to the type of support provided by the surgical guide (bone, mucosa, tooth-support), and errors during the surgical procedure (fully or partially guided surgery and the surgeon's skill). Moreover, other authors [10] add that errors may also result from the physical properties of the material, as well as from the technologies used for manufacturing surgical guides. They also affirm that the incorporation of metal sleeves and fixation screws in mucosa-supported surgical guides is an important factor in reducing deviations during drilling and implant placement [10,11].

So, the main concern surrounding guided implant surgery is the extent of deviation between the planned and the actual implant placement position.

It is this deviation between the planned and final position of an implant that acts as the measure of accuracy in guided implant surgery [12]. When it comes to assessing accuracy, the most widely used method is the superimposition of preoperative virtual planning images and postoperative CBCT images. The deviation between the planned and the final positioning of the implant in the mouth is evaluated through linear and angular measurements, known as deviation parameters.

The accuracy of the different guided surgery systems has been reviewed in numerous in vivo, in vitro, and ex vivo studies [13–18]. A wide variety of measurements are used and, to date, there is no consensus as to which deviation parameters and methods are to be followed in order to best quantify the accuracy of guided surgery.

Therefore, the aim of this systematic review was to assess the scientific literature investigating the accuracy of different guided surgery systems and the methods used to quantify the deviations that occur.

2. Materials and Methods

This systematic review was conducted in accordance with PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

2.1. PICO Question

The PICO framework for this study was as follows:

- P (Population): Patients with total or partial edentulism in whom dental implants were placed with guided surgery.
- I (Intervention): Placement of dental implants using surgical guides.

- C (Control): Methods used to compare the presurgical virtual planning location of the implant with the actual postoperative position.
- O (Outcome): Angular deviation and coronal and apical lineal deviations of the placed implants.

2.2. Search Strategy

An electronic search was conducted for studies published between January 2013 and June 2024. A cross-sectional search of the studies identified was also performed.

A set of Medical Subject Heading (MeSH) terms, keywords, and other free terms were used in the search; Boolean operators (OR, AND) were used to combine the search terms as follows:

- PubMed/MedLine: ((((((surgery, computer-assisted OR dental implant navigation) OR guided dental implant surgery) OR dental stereolithography) AND dimensional measurement accuracy) AND treatment outcome) AND mouth edentulous) OR jaw edentulous.
- MeSH Terms: dental implants; mouth edentulous; dimensional measurement accuracy; stereolithography; surgery computer-aided; surgical procedures operative; mouth; jaw.
- Cochrane database: ((((((surgery, computer-assisted) OR dental implant navigation) OR guided dental implant surgery) OR dental stereolithography) AND dimensional measurement accuracy) AND mouth edentulous) OR jaw edentulous.

2.3. Eligibility Criteria

Inclusion criteria: in vivo studies, randomized controlled trials (RCTs) and controlled trials (CCTs), prospective and retrospective clinical studies, studies with a minimum sample of 10 patients, studies focusing on accuracy results, studies reporting results of the angular, coronal or apical deviation of implants.

Exclusion criteria: in vitro studies, ex vivo studies, animal studies, split-mouth studies, clinical case series, technical reports, pilot studies, studies unavailable in full text, and studies with unclear results.

2.4. Study Selection

Two independent reviewers (N.M.B. and C.M.M.-P.) made a selection of the studies identified in the electronic search by title and abstract, discarding or including works according to the inclusion and exclusion criteria. When there was any disagreement, or when the abstracts of the studies contained insufficient information or provided unclear information, these were included in the full-text analysis in order to avoid excluding relevant studies. Lastly, the complete texts of those works that fulfilled all criteria were analyzed in detail.

Disagreements regarding data extraction were resolved through discussion and simultaneous reading of the text until mutual agreement between the two reviewers was reached. Inter-reviewer reliability in the selection process and after full-text analysis was calculated (percentage of agreement and Kappa correlation coefficient).

2.5. Data Extraction

The main variables extracted from the studies reviewed were coronal, apical, and angular deviation; the deviation parameters and methods used to quantify these deviations were also extracted.

All variables were entered into data collection tables and classified according to the study design.

2.6. Risk of Bias and Quality Assessment of the Included Studies

The Cochrane Collaboration tool (included in the Cochrane Handbook of Systematic Reviews of Interventions Version 5.1.0, updated in March 2011 by Higgins and Green [19] was used to assess the risk of bias in randomized clinical trials (RCTs). The risk of bias was categorized as:

- Low risk of bias: if all the criteria were known.
- Risk of unclear bias: if one or more criteria were partially known.
- High risk of bias: if one or more criteria were unknown.

The Newcastle–Ottawa scale (NOS) was used to assess the methodological quality of prospective and retrospective studies. This scale has been adapted [20] and used in previous systematic reviews [20–22]. A study may be awarded a maximum of 13 stars/points. This score was categorized as:

- Studies scoring 10–13 stars: high methodological quality.
- Studies scoring 7–9 stars: average methodological quality.
- Studies scoring < 7 stars: low methodological quality.

3. Results

3.1. Study Selection and Data Extraction

The initial electronic search identified 3299 studies in the PubMed database and 602 in the Cochrane Central Register of Controlled Trials. The process of identification, screening, eligibility, and inclusion of the studies is shown in the PRISMA flowchart in Figure 1.

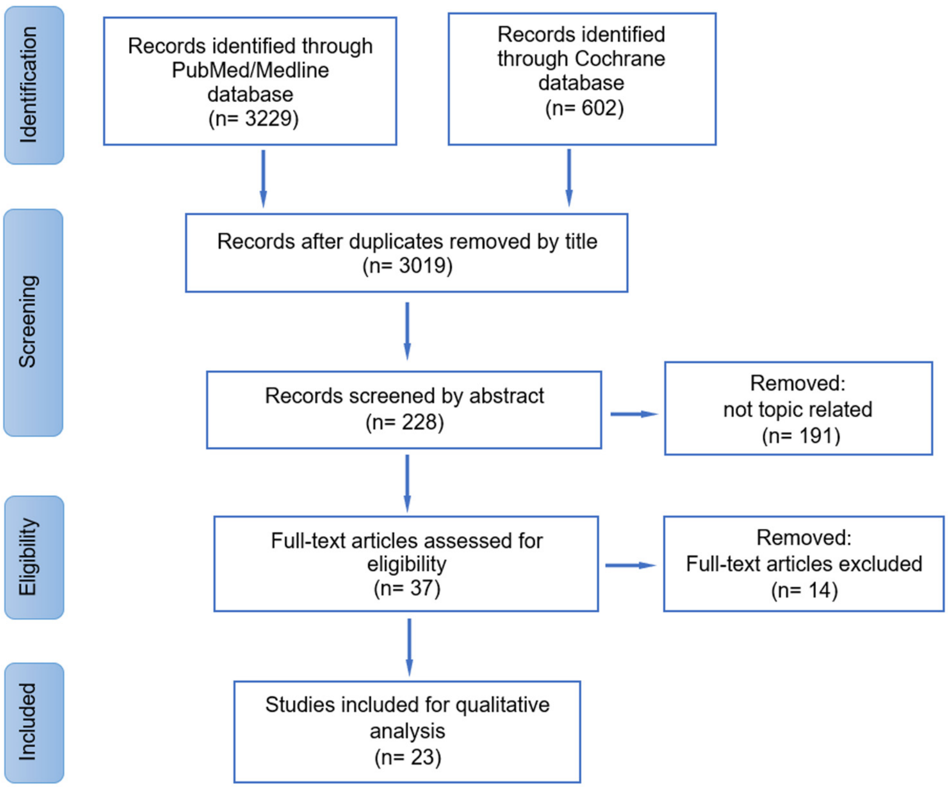

Figure 1. PRISMA flow chart.

A total of thirty-seven studies were selected for full-text analysis, of which 14 were excluded; the reasons for exclusion are detailed in Appendix A Table A1. So, a total of twenty-three studies (five randomized controlled trial [23–27]; thirteen prospective studies [28–40]; and five retrospective studies [11,41–44] that met the inclusion/exclusion criteria were selected for analysis. One study [23] assessed two different guided systems within the same study, so, for the purposes of the review, the results were assessed independently.

Cohen's Kappa statistic between the two reviewers (N.M.B. and C.M.M.-P.) was 0.857 (CI 95%: 0.894–0.819) for title and abstract selection and 0.915 (CI 95%: 0.945–0.885) for full-text assessment. Therefore, the level of agreement was considered strong and almost perfect, respectively.

3.2. Characteristics of the Included Studies

The main results extracted from the studies are summarized in Table 1.

Table 1. Characteristics of the included studies.

Author (Year)	Study Design	No. of Patients	No. of Implants	Edentulism	Type of Support	Flapless	Fixed Screws	Guide System	Deviation Parameters	Method Measurement	Software Measurement
Ochi et al. (2013) [29]	PROS	15	30	Fully	MS	Yes	Yes	Procera	Global, MD, BL, and depth for the neck, and apex	R-MM	Mimics
Cassetta et al. (2013) [41]	RET	10	111	Fully/ Partially	MS/TS/BS	Yes/No	Yes/No	SimPlant	Angular, global coronal, and apical, lateral, and depth	R-MM	Mimics
Cassetta et al. (2014) [11]	RET	24	172	Fully	MS	Yes	Yes	SimPlant	Angular and global coronal	R-MM	Mimics
Stübinger et al. (2014) [28]	PROS	10	44	Fully	BS	No	Yes	Facilitate	Angular, global coronal, and apical, lateral, and depth	R-MM	Mimics
Vercruyssen et al. (2014) [23]	RCT	59	311	Fully	MS/BS	Yes/No	Yes	SimPlant	Angular and global coronal, and apical	R-MM	Mimics
Cassetta et al. (2014) [42]	RET	20	225	Fully	MS	Yes	Yes	SimPlant	Angular, global coronal and global apical	R-MM	Mimics
Zhao et al. (2014) [33]	PROS	11	31	Partially	TS	NR	NR	SimPlant	Angular and linear (apex and shoulder)	R-MM	SimPlant
Testori et al. (2014) [34]	PROS	25	117	Fully Partially	MS/TS/BS	NR	NR	SimPlant	Angular, apical, and platform	R-MM	Mimics
Verhamme et al. (2015) [32]	PROS	25	150	Fully	MS	Yes	Yes/No	Procera Clinical Design	3D, BL, and MD for the tip, shoulder, angle, and depth	R-MM	NobelGuide Validation (v. 2.0.0.4)
Sun et al. (2015) [30]	PROS	15	80	Fully	MS	Yes	NR	Procera (Nobel Biocare)	Angular, global, lateral, and vertical	R-MM	Procera™
Verhamme et al. (2015) [31]	PROS	30	104	Fully	MS	Yes	Yes/No	Procera Clinical Design®	3D, BL, and MD for the tip, shoulder, angle, and depth	R-MM	NobelGuide Validation
Shen et al. (2015) [35]	PROS	30	57	Partially	TS	NR	NR	SimPlant	Angular, shoulder, apex, and depth	R-MM	SimPlant
Van de Wiele et al. (2015) [36]	PROS	16	76	Fully	MS	Yes	Yes	SimPlant	Angular, MD, BL, depth, and global for coronal and apical	R-MM	Mimics
Vercruyssen et al. (2016) [24]	RCT	15	90	Fully	MS	Yes	Yes	SimPlant	Angular, global, BL, MD, vertical, horizontal, and depth	R-MM	Mimics
Verhamme et al. (2017) [37]	PROS	12	72	Fully	MS	Yes	Yes	Maxilim	3D, BL, MD for tip, shoulder, angle, and depth	R-MM	NobelGuide Validation
Schnutenhaus et al. (2018) [44]	RET	56	112	Partially	TS	Yes	No	SMOP	Radial, height and axial deviation	DRM	Geomagic Studio. v9.
Smitkarn et al. (2018) [25]	RCT	52	60	Partially	TS	No	NR	coDiagnostiX	Angular; 3D, MD, BL, AC for shoulder and apex.	R-MM	coDiagnostiX (v9.7)
Younes et al. (2018) [26]	RCT	32	71	Partially	TS	Yes	No	SimPlant	Angular; global, lateral, and vertical for coronal and apex.	R-MM	Mimics
Albeiro et al. (2019) [43]	RET	20	114	Totally	MS	Yes	Yes	SimPlant	Angular, global coronal and apical, and lineal depth	R-MM	Mimics
Derksen et al. (2019) [38]	PROS	66	149	Partially	TS	Yes/No	No	coDiagnostiX	Angular and 3D for an entry point and apex	DRM	coDiagnostiX
Lou et al. (2021) [27]	RCT	60	92	Partially	TS	No	No	3 Shape Implant Studio	3d angular, coronal, apical, and depth	R-MM	3 Shape Implant Studio
Gargallo—Albiol et al. (2021) [39]	PROS	30	60	Partially	TS	No	No	coDiagnostix	Angular; 3D, MD, BL, AC for shoulder and apex	R-MM	coDiagnostiX
Di Giacomo et al. (2022) [40]	PROS	11	50	Totally	MS	NR	Yes	ImplantViewer 1.9	3D angular and lateral coronal and apical	R-MM	Rhinoceros 4.0

No.: number; RCT: randomized controlled trial; RET: retrospective; PROS: prospective; NR: not reported; MS: mucosa-supported; TS: tooth-supported; BS: bone-supported; MD: mesiodistal; BL: buccolingual; AC: apicocoronal; R-MM: radiographic—matching method; DRM: digital registration method. Risk of Bias of the randomized trials.

The studies included a total of 644 patients. The total number of dental implant placements with guided surgery was 2005. In all the studies except two [25,27] in which mucosa- or tooth-supported guides were used, surgeries used a flapless approach. One study [34] used both flapless and open-flap implant placement depending on the keratinized tissue available. Four studies [33–35,40] did not provide this information.

3.3. Risk of Bias of the Randomized Trials

Five RCTs [19–23] were assessed using the Cochrane Collaboration tool. These presented low risk in random sequence generation but incomplete outcome data, selective reporting, and other biases. Three studies [19,22,23] reported that accuracy assessments were performed by an independent blinded researcher, so these works presented a low risk in the blinding of outcome assessment. Regarding allocation concealment and the blinding of participants and personnel, these conditions were not reported, so the risk of bias was unclear according to the Cochrane Handbook.

3.4. Methodological Quality Assessment of the Observational Studies

Assessed with the Newcastle–Ottawa Scale, 10 studies received 10–13 stars [25,26,32,34–36,38–41] indicating a high level of methodological quality, and eight studies [24,27–31,33,37] showed medium-level methodological quality. In all studies, the representativeness and selection of the patients submitted to guided surgery, data collection (preoperative and postoperative images data), comparability of patients on the basis of the study design or analysis, evaluation of results, assessment of accuracy outcomes, adequacy of patient follow-up and appropriateness/validity of statistical analysis, was reported adequately. Regarding sample size calculation, the study by Albiero et al. [40] was the only one that clearly reported this process. Inclusion/exclusion criteria were not described in seven studies [26–29,33,37,40]. Two studies [30,37] did not report the unit of analysis in the statistical model. Training/calibration of assessors of clinical outcomes was reported in only seven studies [24,25,32,36,37,40,41]. Management of confounders via statistical regression models was not reported in any study.

3.5. Methods Used for Quantifying Deviation Parameters

Twenty-one studies [19–33,35–40] used the “radiographic matching method” to assess accuracy. This consists of superimposing the Standard Tessellation Language (STL) files generated in preoperative implant planning over Digital Imaging and Communications in Medicine (DICOM) files generated from postoperative CBCTs of the placed implants. Two studies [34,41] used the “digital registration method”, which consisted of superimposing the STL files used in preoperative implant planning over STL files generated by postoperative scanning of the placed implants.

The programs used for measuring deviation parameters were: Mimics [19,20,22,24,25,30,32,37–40]; CodiagnostiX [21,34,35]; SimPlant [29,31]; Nobel Guide® [27,28,33]; Procera (Nobel Biocare) [26]; Rhinoceros 4.036; 3Shape Implant Studio [23]; Geomagic Studio [41] (Table 1).

Deviation parameters were measured mainly at coronal and apical site levels, in mesiodistal, buccolingual, and apico-coronal directions. The measurements considered were linear, three-dimensional (3D), and angular deviations. These deviation parameters were presented as mean values and standard deviations (SD).

3.6. Accuracy Analysis

The implant planning software programs used in the studies reviewed were SimPlant® [19,20,22,29–32,37–40]; Procera Clinical Design® [25–28]; Facilitate™ [24]; CoDiagnostix® [21,34,35]; ImplantViewer [36]; SMOP [41]; Maxilim [33]; and 3Shape Implant Studio [23]. With respect to the types of guide support used, mucosa-supported surgical guides were the most commonly used. Two studies [30,37] compared three types of surgical guide (mucosa-, tooth- and bone-supported), one study [19] compared two types of guide supports, 11 studies [20,25–28,32,33,36,38–40] used only mucosa-supported guides, eight studies [21–23,29,31,34,35,41] used only tooth-supported guides, and one study [24] used bone-supported guides exclusively.

Deviation parameter data are summarized in Table 2. Angular deviations of placed implants, corresponding to different mandibular or maxillary locations, were described in 22 studies. The mean angular deviation of mucosa-supported guides among the studies ranged from 2.71° (minimum) to 5.14° (maximum). With bone-supported guides, it ranged from 2.49° to 5.08° and with the tooth-supported guides from 2.5° to 5.62°. Measurements of coronal deviations were described in 22 studies. The mean coronal deviations of mucosa-, bone- and tooth-supported guides ranged from 0.87 mm to 2.05 mm, 0.71 mm to 1.60 mm, and 0.39 mm to 1.63 mm, respectively. Measurements of apical deviations were described in 21 studies. The mean apical deviations of mucosa-, bone- and tooth-supported guides ranged from 1.08 mm to 2.28 mm, 0.77 mm to 1.65 mm, and 0.28 mm and 1.84 mm, respectively.

Table 2. Results of deviation parameters.

Authors (Year)	No. of Implants Evaluated	Type of Support	Angular Deviation (°, Mean ± SD)	Coronal Deviation (mm, Mean ± SD)	Apical Deviation (mm, Mean ± SD)
Ochi et al. (2013) [29]	30	Mucosa	-	0.89 ± 0.44	1.08 ± 0.47
Cassetta et al. (2013) [41]	111	Mucosa Bone Tooth	4.71 5.08 3.35	1.63 1.18 1.10	2.10 1.62 1.36
Cassetta et al. (2014) [11]	172	Mucosa	4.33 ± 1.42	1.10 ± 0.39	-
Stübinger et al. (2014) [28]	44	Bone	2.49 ± 0.97	0.71 ± 0.399	0.77 ± 0.382
Vercruyssen et al. (2014) * [23] (I)	55 53	Mucosa Bone	2.86 ± 1.60 3.79 ± 2.36	1.23 ± 0.60 1.60 ± 0.92	1.57 ± 0.71 1.65 ± 0.82
Vercruyssen et al. (2014) * [23] (II)	52 49	Mucosa Bone	2.71 ± 1.36 3.20 ± 2.70	1.38 ± 0.64 1.33 ± 0.82	1.60 ± 0.70 1.50 ± 0.72
Cassetta et al. (2014) [42]	225	Mucosa	4.67 ± 2.68	1.68 ± 0.6	2.19 ± 0.83
Zhao et al. (2014) [33]	13 18	Tooth Mucosa	3.99 5.14	0.90 -	1.23 -
Testori et al. (2014) [34]	43	Mucosa Bone Tooth	4.06 ± 2.82 3.19 ± 1.95 2.94 ± 1.84	1.12 ± 0.65 1.33 ± 0.47 1.63 ± 0.98	1.36 ± 0.64 1.40 ± 0.43 1.84 ± 1.00
Verhamme et al. (2015) [32]	150	Mucosa	3.926 ± 0.414	1.963 ± 0.232	2.288 ± 0.269
Sun et al. (2015) [30]	80	Mucosa	3.33 ± 2.32	-	-
Verhamme et al. (2015) [31]	104	Mucosa	2.819	1.368	1.587
Shen et al. (2015) [35]	57	Tooth	4.21 ± 1.91	1.18 ± 0.72	1.43 ± 0.74
Van de Wiele et al. (2015) [36]	75	Mucosa	2.8 ± 1.5	0.87 ± 0.50	1.10 ± 0.53
Vercruyssen et al. (2016) [24]	90	Mucosa	2.7	0.8	1.1

Table 2. *Cont.*

Authors (Year)	No. of Implants Evaluated	Type of Support	Angular Deviation (°, Mean ± SD)	Coronal Deviation (mm, Mean ± SD)	Apical Deviation (mm, Mean ± SD)
Verhamme et al. (2017) [37]	72	Mucosa	5.018 ± 0.197	2.052 ± 0.074	1.595 ± 0.074
Schnutenhaus et al. (2018) [44]	122	Tooth	4.8 ± 3.1	1.2 mm ± 0.7	1.8 mm ± 0.9
Smitkarn et al. (2018) [25]	30	Tooth	3.1 ± 2.3	1.0 ± 0.6	1.3 ± 0.6
Younes et al. (2018) [26]	21	Tooth	2.30	0.73	0.97
Albeiro et al. (2019) [43]	54	Mucosa	3.16 ± 1.79	1.12 ± 0.52	1.36 ± 0.68
Derksen et al. (2019) [38]	145	Tooth	2.72 ± 1.42	0.75 ± 0.34	1.06 ± 0.44
Lou et al. (2021) [27]	30	Toth	2.05 ± 0.45	0.39 ± 0.12	0.28 ± 0.09
Gargallo—Albiol et al. (2021) [39]	60	Tooth	5.62	1.19	1.77
Di Giacomo et al. (2022) [40]	50	Mucosa	4.58 ± 2.85	0.87± 0.49	1.37 ± 0.69

*: These studies evaluated two different groups in the same study; SD: Standard deviation.

4. Discussion

The present study reviewed the scientific literature dealing with the accuracy of guided implant placement surgery. In addition, the review recorded the deviation parameters measured, and the methods used to quantify these deviations. The study only analyzed in vivo clinical studies, excluding in vitro and ex vivo studies due to their non-representation of real clinical situations. The authors of ex vivo studies [16,17,45] have commented that the conservation and handling of specimens (frozen and thawed) cause modifications to the properties of tissues. This can interfere with the adjustment of radiographic and surgical guides and the positioning of the implants, probably increasing deviations during implant installation [3]. In vitro studies show that there is greater accuracy in the placement of implants in preclinical models. This is because there is no interference from oral anatomy (tongue, oral mucosa, and other factors), which contributes to a greater stability of the surgical guide. In the systematic reviews and meta-analysis published by Jung et al. [46] and Assche et al. [47] the accuracy of guided surgery was evaluated, comparing in vivo, ex vivo, and in vitro models. Both authors agreed that implants placed directly in the mouth (in vivo) presented average deviations greater than those placed in cadavers (ex vivo) and models (in vitro), where greater accuracy was achieved.

The quality of the studies included in the present review suffered some limitations. Of the twenty-three studies, only five were RCTs. There is a clear need to perform more RCTs to reduce risks of bias and improve the quality of evidence. This limitation has also been described in the systematic review and meta-analysis by Raico et al. [21]. Regarding the risk of bias in the RCTs reviewed, important criteria (such as concealment of allocation and blinding of participants, personnel, and outcome assessment) were not reported, so the risk of bias was unclear.

Of the eighteen observational studies included, ten were categorized as high quality, whereas the other eight were of medium quality. No study, except one [40], reported sample size calculation, so the number of patients included in each study, selected consecutively, could affect the reliability of the results depending on the particularities of the study hypothesis. Future studies must follow CONSORT guidelines (Consolidated Standards of Reporting Trials) in order to improve the methodological and scientific quality of trials.

Although the accuracy of guided surgery continues to improve, linear and angular deviations persist. The literature indicates that these deviations are the result of errors that accumulate from the acquisition of CBCT and STL images for virtual planning to the execution of the surgical procedure. Various guided surgery protocols have been designed in order to reduce errors in implant placement and control the variables involved. Several studies have compared pilot drill-guided, partially guided, and fully guided implant surgery [25–27]. Others compare the different types of surgical guide support (bone, mucosa, and tooth support) [23,34,41]. It is evident that there are a variety of possible factors that influence the accuracy of guided surgery, ranging from the most evident, such as the surgeon's experience when performing the surgical procedure, to the less evident, such as the physical properties of the materials used to manufacture surgical guides. In recent years, special interest has been placed on evaluating the influence of the surgeon's experience. In this context, Marei et al. [9] evaluated the accuracy of implants placed with tooth-supported surgical guides and concluded that the group of expert surgeons performed a more accurate implant placement compared with novice surgeons. Regarding the manufacture of surgical guides, most are currently manufactured using CAD/CAM technology [48], either by additive methods (stereolithography laser, digital light processing, selective laser sintering) or subtractive methods such as milling. Stereolithographic 3D printed surgical guides are the most frequently used, although milling seems to achieve greater accuracy and better outcomes according to Rodríguez et al. [10].

Two methods for assessing the accuracy of guided surgery were described in this review. The first and most widely used was the "radiographic-matching method", in which STL files of the planned implant positions were superimposed over DICOM files obtained from a postoperative CBTC scan. However, exposing patients to a second CBCT to determine the final implant position is controversial since the use of CBCT images after implant insertion should be restricted to a small number of indications: for evaluating graft healing, assessing complications related to neurovascular trauma, or monitoring complex surgical procedures [49]. CBCT scans are not considered appropriate for routine monitoring. Likewise, exposing patients to a second dose of radiation does not fulfill radiological safety standards [50] according to the ALARA (As Low As Reasonably Achievable) principle. Previous studies have also indicated that voxel size, metal implant artifacts, patient movement, and scanning parameters directly influence CBCT image quality and so affect the accuracy of these images' superimposition, limiting their usefulness [49,51].

The "digital registration method" has been proposed as an alternative method that avoids a second postoperative CBCT scan and overcomes the disadvantages described above [34,41]. In this method, the postsurgical implant positions are determined with a digital impression of scan bodies/transfers connected to the placed implants. The STL files resulting from preoperative virtual planning are superimposed on the STL files generated from the postoperative digital scan. This digital method can avoid the effects of CBCT quality on data registration accuracy [41].

Although both methods offer alternatives intended to reduce the accumulation of error, a recent in vitro study by Yi et al. [47] compared these two methods in terms of their capacity to assess the accuracy of guided surgery implant placement, concluding that both digital registration and conventional radiographic methods achieve good agreement using tooth-supported surgical templates. Likewise, analyzing the deviation data obtained in the studies included in the present review, the deviation ranges obtained with the two methods were comparable (Table 2). Nevertheless, it should be noted that the quality of postoperative images constitutes a factor that could prejudice the quantification of deviation parameters.

The deviation parameters analyzed in this review were 3D angular deviations and global coronal and apical deviations since these were the ones reported in all the studies. Additionally, several authors [20,21,25,27,28,32,33,35] measured other linear parameters in the mesiodistal (MD), buccolingual (BL), and apico-coronal (AC) directions, allowing them to obtain more conclusive evidence regarding the sources of deviation. Verhamme et al. [33] report interesting findings regarding these linear measurements, whereby deviation in the BL direction has a significant impact on apical, coronal, and depth deviations, while deviations in the MD direction also have a significant impact on apical, coronal, and angular deviation.

Comparing the accuracy of guided surgery in relation to the type of tissue support, a variety of results were reported. In the retrospective study by Cassetta et al. [37], 10 adults were included, and 111 implants were available for a comparison of accuracy. With respect to surgical guide support, bone-supported guides (1.62 mm) provided better accuracy than mucosa-supported guides (2.10 mm) in apical deviation, while tooth-supported guides (1.36 mm apical, and 1.10 mm coronal) achieved greater accuracy than mucosa-supported guides (2.10 mm apical, and 1.63 mm coronal) in apical and coronal deviations. Overall, the present review found significantly better accuracy using tooth-supported guides. In the same way, in the multicenter clinical study by Testori et al. [30], 25 patients were treated, placing a total of 117 implants using CAD/CAM surgical guides supported by mucosa, bone, and/or teeth. The results of this clinical study showed that implant placement using bone- and mucosa-supported guides was more accurate compared with tooth-supported guides or a combination of tooth and mucosa, although the differences were not statistically significant. When the three types of surgical guides (mucosa-, tooth- and bone-supported) were compared, findings were inconclusive due to the fact that only two studies made this comparison. However, the systematic review and meta-analysis by Raico et al. [17] suggests that there is an association between guide support and the clinical accuracy of computer-guided implant surgery. Tooth-supported guides exhibited greater accuracy than bone and mucosa-supported guides. It would appear that the surgical guide does influence the deviation of the implant placement depending on whether the supporting tissue is soft or hard. The interpretation and measurement of soft tissue at the planning stage, together with the stability offered by hard tissues during the surgical procedure, may be the key determinants for greater precision in guided surgery.

Finally, the capacity of a software program to accurately detect the bone-soft tissue interface and record linear measurements is a fundamental requirement if it is to perform the complex tasks involved in virtual implant placement and surgical guide design adequately. Increasing numbers of software programs are available for processing and analyzing CT images. So, a variety of different software programs were used in the studies included in this review for both planning and measuring linear and angular deviations. Nevertheless, it should be noted that the deviation ranges observed in this review did not vary widely despite the diversity of software used. In this regard, a study published by Al-Ekrish et al. [52], compared three types of software (Blue Sky Plan, coDiagnostiX, and RadiAnt) to assess the accuracy of linear measurements on CBCT images, concluding that, although all three software programs exhibited significant measurement errors of between 0.43 and 0.56 mm, no significant differences were identified between any of the programs. It would be intersting to study the accuracy of other widely used guided surgery system such as Avinent and ZimVie using this approach.

Limitations

One limitation of the present literature review was the heterogeneity of the guided surgery protocols used in the studies analyzed. As there was no consensus regarding the planning software used, the techniques employed to manufacture surgical guides, or the deviation parameters used to measure the accuracy of guided surgery, it was only possible to perform a qualitative analysis of the studies.

The quality of the studies reviewed was another limitation. Only five of the studies were RCTs, pointing to a clear need for studies designed to minimize the risk of bias and so improve the quality of evidence.

5. Conclusions

According to the data analyzed in this systematic review, all systems exhibit some errors. The minimum and maximum deviation ranges found between the implants planned and placed by guided surgery show that, although deviations occur, guided surgery is not far from accurate. Standardizing the working protocols and methods for assessing accuracy in future studies, would make it possible to evaluate and control the variables that influence the accuracy of this technique in a more conclusive way.

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Appendix A

Table A1. Characteristics of eligible studies not included.

Author—Year	Study	Exclusion Reason
Cassetta et al., 2013 [53]	Is it possible to improve the accuracy of implants inserted with a stereolithographic surgical guide by reducing the tolerance between mechanical components?	Sample < 10 patients
Cassetta et al., 2015 [54]	The Influence of the Tolerance between Mechanical Components on the Accuracy of Implants Inserted with a Stereolithographic Surgical Guide: A Retrospective Clinical Study	Patient data are not clear
Cassetta et al., 2013 [55]	The intrinsic error of a stereolithographic surgical template in implant-guided surgery	Describe mixed results for the three types of surgical guides
Vieira et al., 2013 [56]	Clinical accuracy of flapless computer-guided surgery for implant placement in edentulous arches	Describe results for the maxilla and mandible separately
Vercruyssen et al., 2015 [57]	Depth and lateral deviations in guided implant surgery: an RCT comparing guided surgery with mental navigation or the use of a pilot-drill template	The same authors and the population were used in a previous paper
Sun et al., 2015 [58]	Accuracy of a Dedicated Bone-Supported Surgical Template for Dental Implant Placement with Direct Visual Control	The implants were placed without a surgical guide
Cassetta et al., 2017 [59]	How much does experience in guided Implant surgery play a role in accuracy? A randomized controlled pilot study	The main topic is different
Bencharit et al., 2018 [5]	In Vivo Tooth-Supported Implant Surgical Guides Fabricated with Desktop Stereolithographic Printers: Fully Guided Surgery is More Accurate than Partially Guided Surgery	Unclear description of the number of patients per group

Table A1. *Cont.*

Author—Year	Study	Exclusion Reason
Schneider et al., 2019 [60]	A Randomized Controlled Clinical Trial Comparing Conventional and Computer-Assisted Implant Planning and Placement in Partially Edentulous Patients. Part 4: Accuracy of Implant Placement	Describe results for different kinds of guided surgery
de Oliveira et al., 2019 [61]	Analysis of Linear and Angular Deviations of Implants Installed with a Tomographic-Guided Surgery Technique: A Prospective Cohort Study	Describe results for the maxilla and mandible separately
Vinci et al., 2020 [62]	Accuracy of Edentulous Computer-Aided Implant Surgery as Compared to Virtual Planning: A Retrospective Multicenter Study	Unclear deviation parameters
Tang et al., 2021 [63]	Accuracy of half-way mucosa supported implant guides for edentulous jaws: a retrospective study with a median follow-up of 2 years	Deviation parameters are different
Cunha et al., 2021 [64]	Accuracy evaluation of computer-guided implant surgery associated with prototyped surgical guides	Sample < 10 patients
Kim et al., 2022 [65]	Accuracy of digital surgical guides for dental implants	Describe mixed results for the two types of surgical guides

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