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Precision and trueness of computer-assisted implant placement using static surgical guides with open and closed sleeves: An in vitro analysis

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Abstract

Objectives: The aim of this in vitro study was to determine accuracy defined by trueness and precision of computer-assisted implant surgery comparing two guided surgery kits designed for either closed sleeves or open sleeves with a lateral window.

Material and methods: Each n=20 implants were placed fully guided (sleeve-bone distance of 2 or 4 mm) in identical replicas using a surgical guide with both closed sleeve or an open sleeve, partially guided, or free hand. The achieved implant position was digitized and compared with the planned position. Trueness and precision were determined. The angular deviation was defined as the primary outcome parameter. The means, standard deviation, and 95%-confidence intervals were analyzed statistically with 1-way ANOVA and the Scheffé procedure.

Results: The accuracy of guided implant placement using closed and open sleeves was comparable when the sleeve-bone distance was 2 mm. Accuracy decreased when the sleeve-bone distance increased in both fully guided groups, more so in the open than in the closed sleeve group. The least accurate method was the free-hand group. Partially guided implant surgery was more accurate than free-hand placement, but less accurate than the fully guided groups with 2-mm sleeve-bone distance.

Conclusions: The closer the sleeve to the bone, the more accurate and precise is computer-assisted implant surgery using a closed system and a system using open sleeves. Partially guided implant surgery using only the static guide for the pilot drill is less accurate than both fully guided approaches, but more accurate than free-hand surgery.

KEYWORDS
accuracy, computer-assisted implant surgery, guided implant surgery, open sleeve, precision, surgical stent, trueness

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1 | INTRODUCTION

Malpositioning of dental implants, one of the main reasons for future hard- and/or soft-tissue loss (Hämmerle & Tarnow, 2018), represents a restorative challenge, might result in compromised esthetic results (Evans & Chen, 2008), and can be hard to clean, which may lead to future peri-implant inflammation (Canullo et al., 2016). This might also result in immediate surgical complications when the implant is mispositioned, for example, nerve damage, perforation of the cortical plate, or damage of adjacent teeth (Tatakis et al., 2019).

Computer-assisted implant surgery (also referred to as guided implant surgery) was shown to be more accurate to transfer the planned implant position than a free-hand implant placement procedure (Guentsch et al., 2021; Tahmaseb et al., 2018; Tattan et al., 2020; Van Assche et al., 2012; Vercruyssen, Hultin, et al., 2014; Zhou et al., 2018). Guided implant surgery can be performed by using (i) static guides that rest on the remaining dentition and/or soft tissue and bone, with sleeves and keys depending on the specific implant system or by using (ii) navigated systems where a camera surveils the position of the handpiece in 3-dimensional relation to the jaw (Gargallo-Albiol et al., 2020; Vercruyssen et al., 2014). When static guides are used, the operator has the possibility (i) to use the guide for the osteotomy and to place the implant fully guided through the guide, (ii) to use the guide only for preparing the implant bed, placing the implant free hand, or (iii) to use the guide for the pilot drill only to find the appropriate position and to perform the remaining osteotomy and the implant placement free hand (Gargallo-Albiol et al., 2020). Using a static guide for the pilot drill delivers more accurate implant positioning than performing the implant surgery free hand, but it is still less accurate than the fully guided approach (Guentsch et al., 2021).

The accuracy of guided implant surgery using static guides is impacted by several factors: (i) the sleeve height (El Kholy et al., 2019; Naziri et al., 2016), (ii) the bone-to-sleeve distance (Guentsch et al., 2021; Park et al., 2009), (iii) the height of the surgical key (El Kholy et al., 2019; Koop et al., 2013), (iv) the presence or absence of teeth for supporting the surgical guide (Ersoy et al., 2008; Kessler et al., 2021; Schnutenhaus et al., 2018), and (v) if a flap or flapless approach is chosen (Vasak et al., 2011; Zhou et al., 2018). Another clinical aspect to consider is the anatomic location of the implant to be placed, with smaller deviations in the anterior area than in posterior sites (Vasak et al., 2011). A limited interocclusal distance to perform guided implant placement is a known intraoperative complication or limitation (Jung et al., 2009). Recent studies suggest that lateral open sleeves might be bringing clinical advantages in posterior sites and in patients with limited interarch distance (Tallarico et al., 2019). The sleeves are usually C-shaped with the open part facing buccally (Oh et al., 2021). This may also allow for better water irrigation and cooling of the bur (Salomo-Coll et al., 2021). This raises the question if these benefits are achieved at the expense of the accuracy of the guided system. Accuracy is defined by the trueness (planned vs. actual position) and the precision (difference among implants) of a method (ISO-5725-1:1994 (E),2018).

The aims of this in vitro study were (a) to assess precision and trueness of a guided surgery system that uses closed sleeves versus a system with a sleeve that has a lateral window (open sleeve) and (b) to compare their accuracy against free-hand implant placement and partially guided placement (pilot drill only). The null hypothesis was that the kind of sleeve system, open or closed, has no impact on the accuracy of implant placement.

2 | MATERIAL AND METHODS

2.1 | Experimental preparations

The experimental set-up was described recently (Guentsch et al., 2021). In brief, 120 identical mandibles were replicated from a cone-beam computed tomography (CBCT) scan of a partially edentulous patient who lost a mandibular right first molar (IRB approved protocol#: HR-1807025341). A standard tessellation language (STL) file of the mandible was generated from the 3D image data set of the CBCT. The STL file was transferred for stereolithographical printing (Grey resin version 4 using the Form 3B printer; all Formlabs Inc) of identical replicas.

An implant planning software program (coDiagnostiX; Dental Wings GmbH) was used to virtually plan a single implant (Bone level tapered 4.1×10 mm; Institut Straumann AG) for the mandibular right first molar position. Standardized surgical guides extending over 3/4 of the mandible (lower left canine to lower right second molar) were designed for the planned implant at the bounded edentulous space. All guides were 3D-printed with a Class I biocompatible resin (Surgical Guide resin, Formlabs Inc). Surgical guides for fully guided implant surgery were planned for (i) either a Ø5 × 5-mm guided sleeve (T-sleeve; Institut Straumann AG) to represent the "closed sleeve" group, (ii) a Ø5.25 × 6-mm C-guide sleeve (Size M, Versah) to represent the "open sleeve" group. The sleeve heights specified the free distances of the sleeve-to-bone levels of 2 and 4 mm (coded as H2 and H4). For the partially guided group, a sleeve with a Ø2.2 × 6 mm (drill sleeve with funnel; steco-system-technik GmbH) was used, corresponding to the diameter of the pilot drill. The sleeve-to-bone distance for this guide was 2 mm.

2.2 | Treatment groups

The sequential drilling of all osteotomies in the closed sleeve groups was performed according to manufacturer's recommendations for the standard fully guided system (Figure 1A). The implants were placed through the guide. In the open sleeve groups, the drilling sequence of Densah burs (Versah) followed the appropriate implant reference guide for Straumann implants. The pilot drill and the VT1828 drill were used with a G-Stop Vertical Gauge Medium and 5 mm, 10 mm, and 13 mm G-Stop Keys, to allow initially continuous key-sleeve guidance (Figure 1B). The remaining drills were used with a G-Stop Vertical Gauge Medium and 13 mm G-Stop Keys. All drills were used in the

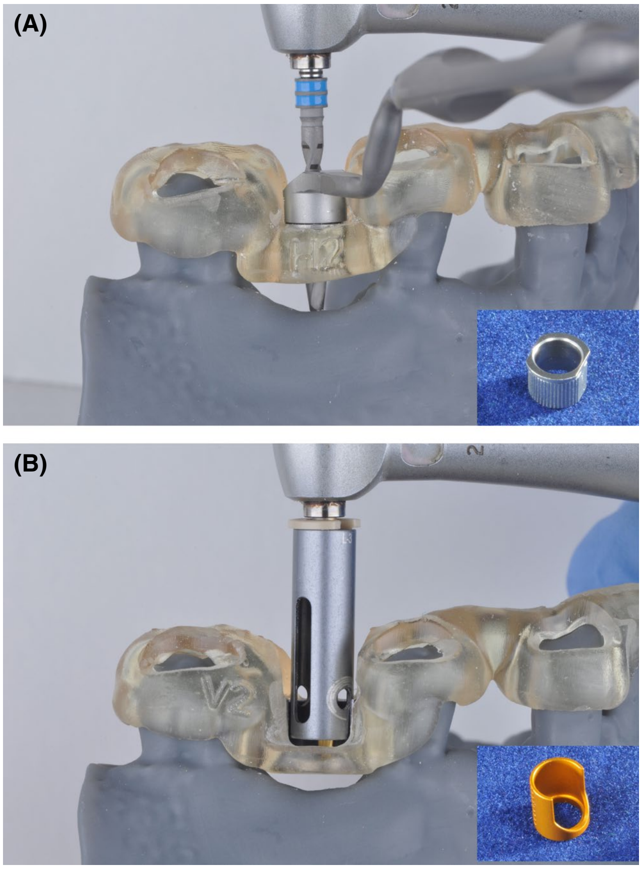

FIGURE 1 Experimental set-up: replica of a mandible with a static surgical guide for the Straumann system using a closed sleeve with inserted key handle and drill in place (a) in comparison to the Versah guided surgery system with an open sleeve with lateral window and with a vertical stop. The keys come in different length, are attached to the drill and follow a sequence that is depending on the planned implant position (b)

clockwise cutting mode. The implants were placed without the guide. The static guide in the partially guided group was only used for the pilot drill. The remaining drilling sequence was performed free hand. No guide was used in the free-hand group. The full surgical drilling sequence was performed free hand and the best effort was made to reproduce the implant position planned for other groups. All surgical procedures were performed by the same operator for consistency.

2.3 | Data acquisition

The achieved implant positions were digitized using a dental laboratory scanner (E4 scanner, 3shape) with accuracy of 4 μm (claimed by the manufacturer) and an implant scanbody (Cares RC Scanbody 4.1 × 10 mm, Straumann). Virtually planned (reference) and postoperative implant STL files were superimposed using a best-fit algorithm and compared with the treatment evaluation tool of the planning software. The International Organization for Standardization (ISO) standard 5725 uses the terms trueness and precision to describe accuracy (ISO-5725-1:1994 (E),2018). Trueness refers to the closeness of the agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. Precision refers to the closeness of the agreement between test results. A method can be considered accurate, when trueness and precision are high. The 3D deviation at the crest and apex of the implant (as root mean square between virtual pre-operative planning and post-operative STL-file) as well as the angular deviation and the mesial–distal, vestibular–oral, and coronal–apical deviation at the crest and apex were evaluated (Figure 2). The treatment evaluation was performed single-blinded (AG).

2.4 | Statistical analysis

In an a priori sample size calculation (using NCSS PASS 2019), the total sample of $n = 120$ achieves 93% power to detect differences among the means versus the alternative of equal means using an F test with a .05 significance level. The size of the variation in the means is represented by the effect size $f = \sigma m/\sigma$, which is 0.40. A post-hoc analysis showed that the power of the study was in fact 99%.

Trueness was determined as difference between actual and planned (=reference) position with each $n = 20$ measurements per group using the magnitude of the values. Precision was calculated as distances between each implant within a group ($n = 191$ values per group). Means, standard deviations, and 95%-confidence intervals were calculated for angulation and position discrepancies. Statistical computations were done using a statistical analyzing software (IBM SPSS Statistics 28). A one-way analysis of variance (ANOVA) was conducted to assess the overall statistical significance of differences among different groups. Scheffe´s multiple comparisons were used to test the differences between the groups.

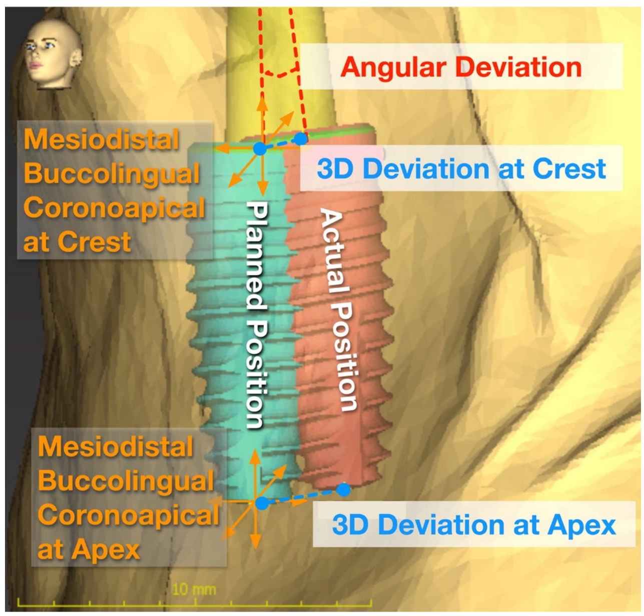

FIGURE 2 Parameters assessed when comparing planned (reference) and actual implant position

3 | RESULTS

Computer-assisted implant surgery, fully or partially guided, achieved a higher accuracy in terms of trueness (planned vs. actual position) and precision (implants among each other) than free-hand surgery and placement (Table 1).

The use of open or closed sleeves for fully guided osteotomies achieved higher trueness for the angle deviation than partially guided implant surgery using the guide only for the pilot drill and free-hand implant surgery and placement (Figure 3). The lowest angle deviation was achieved when the sleeve was closest to the bone. There was no statistically significant difference ($p = 1.00$) between the closed

TABLE 1 Trueness data (as mean and standard deviation (SD) as well as their 95%-confidence interval (CI)) for guides surgery with a guide using a closed sleeve (Straumann) and open sleeve (Versah) in comparison to partially guided implant surgery using a pilot drill or free hand

Trueness As difference to the reference value (Comparing actual vs. planned implant position, $n = 20$ implants each group)		Closed Sleeve (S) Mean (SD) [95%-CI]	Open Sleeve (V) Mean (SD) [95%-CI]	Closed Sleeve (S) Mean (SD) [95%-CI]	Open Sleeve (V) Mean (SD) [95%-CI]	Partially Guided Mean (SD) [95%-CI]	Free Hand Mean (SD) [95%-CI]	*ANOVA*	
Sleeve-Bone Distance		2 mm		4 mm		2 mm	N/A	*F*-value	*p*
Crest in mm	Angle in degree	**1.35**[†∫] (0.64) [1.05–1.65]	**1.49**[†∫] (0.67) [1.17–1.80]	**1.57**[†∫] (0.77) [1.21–1.93]	**1.97**[†∫] (1.03) [1.49–2.45]	**2.83**[*#] (0.79) [2.46–3.19]	**3.58**[*#] (2.01) [2.63–4.52]	13.2	.01
	Δ3D	**0.28**[†∫] (0.16) [0.20–0.35]	**0.29**[†∫] (0.15) [0.22–0.36]	**0.37**[†∫] (0.13) [0.31–0.43]	**0.68**[*$] (0.22) [0.58–0.78]	**0.54**[*$] (0.16) [0.46–0.61]	**0.56**[*$] (0.22) [0.46–0.67]	17.4	.01
	Mesial–distal	**0.08**[†∫] (0.07) [0.04–0.11]	**0.16** (0.15) [0.09–0.23]	**0.09**[∫] (0.09) [0.05–0.13]	**0.43** (0.20) [0.34–0.53]	**0.20**[$] (0.15) [0.13–0.27]	**0.25**[$¶] (0.16) [0.17–0.32]	16.8	.01
	Buccal–lingual	**0.22**[†∫¶] (0.10) [0.18–0.27]	**0.17**[†∫¶] (0.12) [0.11–0.23]	**0.18**[†∫¶] (0.20) [0.09–0.28]	**0.46**[*$] (0.23) [0.35–0.57]	**0.44**[*$] (0.21) [0.34–0.53]	**0.44**[*$] (0.25) [0.33–0.56]	10.7	.01
	Coronal–apical	**0.12** (0.11) [0.09–0.15]	**0.09** (0.09) [0.05–0.13]	**0.13** (0.10) [0.08–0.17]	**0.08** (0.07) [0.05–0.11]	**0.12** (0.09) [0.08–0.16]	**0.12** (0.11) [0.07–0.17]	1.1	.38
Apex in mm	Δ3D	**0.49**[†∫] (0.31) [0.34–0.63]	**0.53**[†∫] (0.20) [0.44–0.62]	**0.55**[†∫] (0.22) [0.45–0.65]	**0.84** (0.40) [0.66–1.03]	**0.97**[*$] (0.25) [0.86–1.09]	**1.03**[*$] (0.61) [0.74–1.31]	8.9	.01
	Mesial–distal	**0.16**[¶†∫] (0.13) [0.09–0.22]	**0.28** (0.25) [0.17–0.40]	**0.22**[¶] (0.18) [0.13–0.30]	**0.53**[*] (0.34) [0.38–0.69]	**0.39** (0.30) [0.25–0.53]	**0.47**[$] (0.31) [0.32–0.61]	6.4	.01
	Buccal–lingual	**0.46** (0.30) [0.32–0.61]	**0.35**[†∫] (0.19) [0.26–0.44]	**0.34**[†∫] (0.36) [0.17–0.50]	**0.56** (0.39) [0.38–0.74]	**0.83**[&§] (0.26) [0.70–0.95]	**0.85**[&§] (0.62) [0.56–1.14]	7.1	.01
	Coronal–apical	**0.12** (0.06) [0.09–0.15]	**0.09** (0.09) [0.05–0.13]	**0.12** (0.09) [0.08–0.17]	**0.08** (0.06) [0.05–0.11]	**0.12** (0.08) [0.08–0.16]	**0.12** (0.09) [0.08–0.16]	1.1	.37

*significant different ($p<.05$) to closed sleeve system.
#significant different ($p<.05$) to open sleeve system.
$significant different ($p<.05$) to H2 closed sleeve system.
&significant different ($p<.05$) to H4 closed sleeve system.
§significant different ($p<.05$) to H2 open sleeve system.
¶significant different ($p<.05$) to H4 open sleeve system.
†significant different ($p<.05$) to partially guided.
∫significant different ($p<.05$) to free hand placement.
S–Straumann Fully Guided Surgery System.
V–Versah Guided Surgery System.
Bold indicates statistically significant *p*-value of $p<.05$.

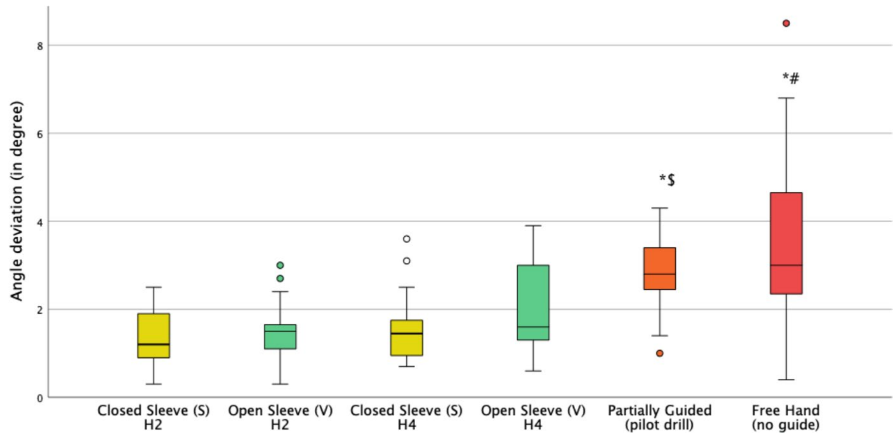

FIGURE 3 Angular deviation for guided surgery with open and closed sleeve, as well as partially guided and free hand. The angular deviation affects the position of the implant. The higher the angular deviation, the higher the distance to the bull's eye (see Figure 4), especially at the implant tip. *$p < .05$, significant different to closed sleeve H2 and H4; #$p < .05$, significant different to open sleeve H2 and H4; \$$p < .05$, significant different to open sleeve H2 only S–Straumann fully guided kit; V–Versah guided surgery system H2–2 mm bone to sleeve distance; H4–4 mm bone to sleeve distance

sleeve group (1.35 ± 0.64°) and the open sleeve group (1.49 ± 0.67°) when the sleeve-bone distance was set at 2 mm. The angular deviation slightly increased when this sleeve-bone distance was increased to 4 mm, but the difference between both groups were not statistically different to the 2-mm sleeve-bone distance nor was the variation significantly different between the closed (1.57 ± 0.77°) and open (1.97 ± 1.03°) group ($p = .93$). In comparison, free-hand implant surgery and placement showed the highest angular deviation with 3.58 ± 2.01° (significantly different to both, closed and open sleeve with 2-mm and 4-mm sleeve-bone distance, $p = .01$).

Partially guided implant surgery using the guide for the pilot drill only showed an angular deviation of 2.83 ± 0.79°, which was significantly higher than the fully guided groups with 2-mm sleeve-bone distance (closed sleeve $p = .004$ and open sleeve $p = .014$, respectively), and the closed sleeve group with 4-mm sleeve-bone distance ($p = .027$). The trueness in regards of angular deviation appeared to be numerically higher for the fully guided group with open sleeve and 4-mm sleeve-bone distance (1.97 ± 1.03°) in comparison to the partially guided group (2.83 ± 0.79°) but statistically this difference was insignificant ($p = .303$).

The mesial–distal and the buccal–lingual deviation of each implant is illustrated in Figure 4. This visualization allows illustration of both, the trueness (the closer to the center, the higher the trueness) and the precision (the closer the values to each other, the higher the precision).

The bull's eye diagrams for the 2-mm bone-to-sleeve distance for the closed (Straumann) and the open sleeve system (Versah) show similar patterns. However, with an increase of the sleeve-bone distance to 4 mm, it shows that the open sleeve system, where there is a lateral window on the buccal site, deviates more toward the lingual and distal direction. The 3D-deviation at the crest level shows that while there is no statistically significant difference between closed and open sleeve group for the 2-mm sleeve-bone distance (0.28 ± 0.16 mm vs. 0.29 ± 0.15 mm; $p = 1.00$), the 3D-deviation for 4-mm sleeve-bone distance is significantly higher in the open sleeve group (0.68 ± 0.22 mm) than in the closed sleeve group (0.37 ± 0.13 mm; $p = .01$).

The differences among the implants in each group represent the precision of the respective method and the results are presented in Table 2. The highest values and therefore lowest precision for the angular deviation was observed in the free-hand group with a distance among implants of 2.25 ± 1.95° and the highest precision for the open and closed sleeve groups with 0.76 ± 0.54° and 0.76 ± 0.60°, respectively ($p = .01$). The free-hand implant surgery appears to be the least reliable.

4 | DISCUSSION

Computer-assisted implant placement using static surgical guides with closed and open sleeves achieved in this in vitro study a higher accuracy in terms of trueness and precision in comparison to free-hand implant surgery and placement. High trueness and precision were determined in both fully guided implant surgery groups, with no statistical difference between the closed sleeve system (Straumann) in comparison with a sleeve that has a lateral window (Versah) when the sleeve-to-bone-distance was lowest (2 mm). However, when the distance between sleeve and bone was increased, the closed sleeve system achieved better results in terms of 3D deviation at the crest and apex. Therefore, our hypothesis that the kind of sleeve system has no impact on accuracy can only be rejected for the scenario that the sleeve-to-bone distance is ≥4 mm. An increase in the sleeve-to-bone distance appears to lead to a decrease in trueness and precision in the open sleeve system.

The accuracy of transferring the planned implant position to the clinical situation relies on several steps, from the fabrication of the surgical guide to the used surgical kits. The particular components of a static surgical guide for computer-assisted implant placement was

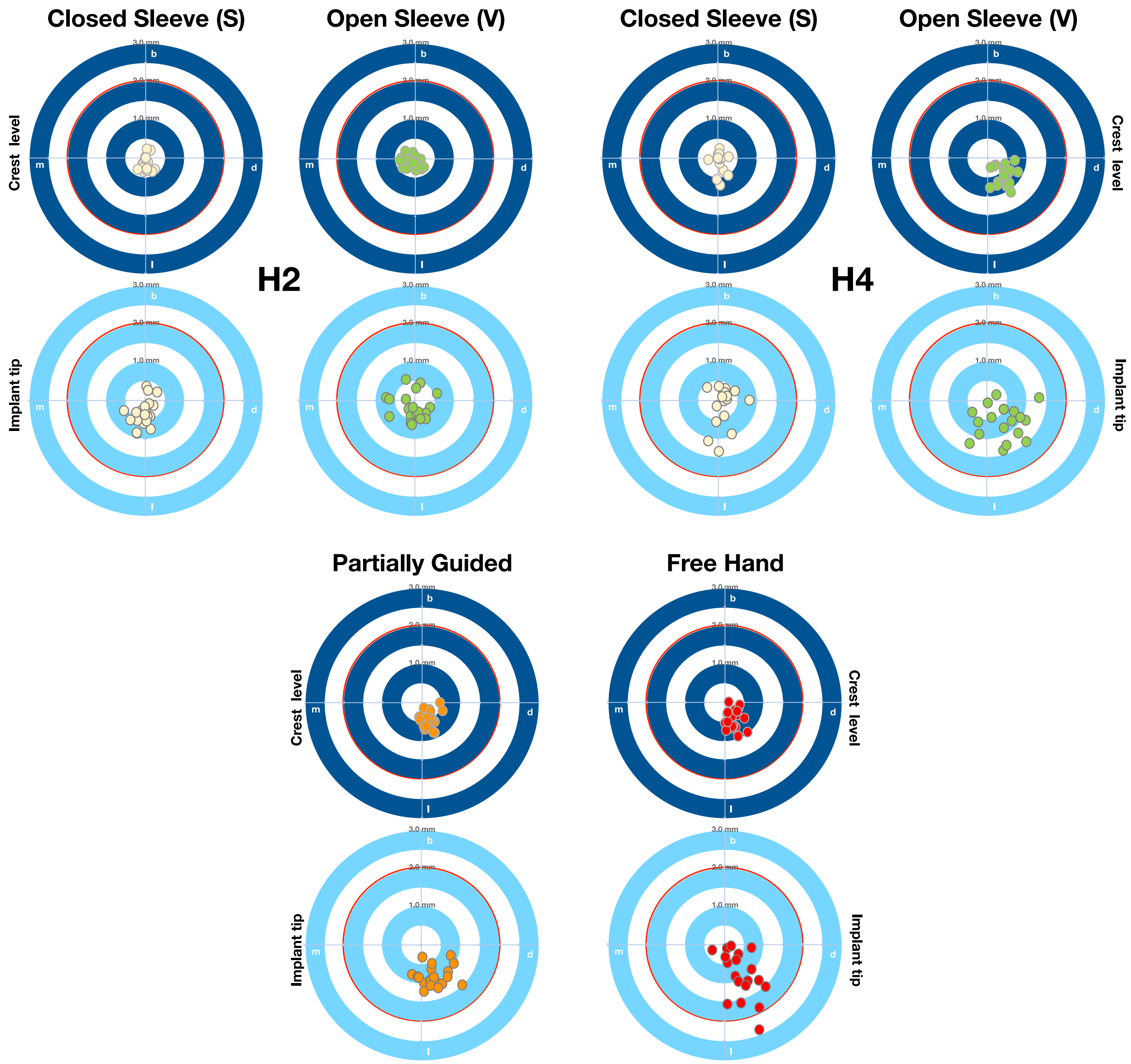

FIGURE 4 Mesio-distal and buccal-lingual implant positions projected on a Bull's Eye. The red ring represents the 2-mm safety-zone. The top row (dark blue) represents the distribution of values at the crest level, and the bottom row (light blue) illustrates the position of the implant tips. Accuracy is defined by trueness and precision. The closer to the bull's eye, the higher the trueness and the closer the values to each other, the higher the precision

investigated by El Kholy et al., who investigated the impact of sleeve-to-bone distance and the drilling distance on the accuracy of implant surgery (El Kholy et al., 2019). The general results showed the further the distance from the guide sleeve to the implant tip, the greater the deviation. This deviation was lessened, however, when the guide key height, or the total length the guide is in contact with the drill, was increased. Relating this information to virtually designing the surgical guide indicates the closer the sleeve is to the planned platform, the greater the potential accuracy. These findings are in alignment with the presented results. The trueness and the precision of implant placement were better for both, the closed sleeve or for the open sleeve with a lateral window, when the sleeve was closer to the bone (sleeve-bone distance of 2 mm). When the sleeve-to-bone distance was increased in the guided surgery groups from 2 mm to 4 mm, the values for angular deviation and any 2D and 3D deviation were advantageous for the closed sleeve system. However, using the surgical guide for the whole drilling sequence (closed or open sleeve) resulted in higher accuracy than pilot drill only or free-hand surgery. This is clinically relevant for the protection of critical anatomic structures and allows for reproducible restorative-driven implant positioning for functional and esthetic outcomes (Widmann & Bale, 2006). Younes et al. concluded their findings of a randomized clinical trial comparing free-handed, pilot-drill guided and fully guided implant surgery in n=32 partially edentulous patients that fully guided implant surgery should be considered the gold standard when perfect implant positioning is required (Younes et al., 2018).

TABLE 2 Precision data (as mean and standard deviation (SD) as well as their 95%-confidence interval (CI)) for guides surgery with a guide using a closed sleeve (Straumann) and open sleeve (Versah) in comparison to partially guided implant surgery using a pilot drill or free hand

Precision As difference or distance among implants (based on *n* = 191 comparisons within each group)		Closed Sleeve (S) Mean (SD) [95%-CI]	Open Sleeve (V) Mean (SD) [95%-CI]	Closed Sleeve (S) Mean (SD) [95%-CI]	Open Sleeve (V) Mean (SD) [95%-CI]	Partially Guided Mean (SD) [95%-CI]	Free Hand Mean (SD) [95%-CI]	*ANOVA*	
Sleeve-Bone Distance		**2 mm**		**4 mm**		**2 mm**	**N/A**	**F-value**	***P***
Crest in mm	Angle in degree	**0.76**[¶∫] (0.54) [0.68–0.83]	**0.76**[¶∫] (0.60) [0.67–0.84]	**0.83**[&∫] (0.73) [0.72–0.93]	**1.32**[*&†∫] (0.90) [1.19–1.45]	**0.91**[¶∫] (0.76) [0.80–1.02]	**2.26**[*#] (1.95) [1.98–2.54]	62.0	.01
	Δ3D	**0.16**[&¶∫] (0.14) [0.14–0.18]	**0.13**[#†∫] (0.10) [0.12–15]	**0.24**[*] (0.17) [0.21–0.26]	**0.23**[*] (0.16) [0.21–0.25]	**0.19**[§∫] (0.15) [0.17–0.21]	**0.25**[*†] (0.21) [0.22–0.28]	17.3	.01
	Mesial–distal	**0.11**[#†∫] (0.09) [0.09–0.12]	**0.20**[*] (0.15) [0.18–0.22]	**0.10**[#†∫] (0.11) [0.09–0.12]	**0.19**[*] (0.13) [0.17–0.21]	**0.20**[*] (0.14) [0.18–0.22]	**0.18**[*] (0.13) [0.16–0.20]	25.2	.01
	Buccal–lingual	**0.18**[∫] (0.15) [0.16–0.20]	**0.17**[∫] (0.12) [0.15–0.19]	**0.24**[#] (0.24) [0.20–0.27]	**0.16**[$†∫] (0.14) [0.14–0.18]	**0.24**[#∫] (0.17) [0.21–0.26]	**0.30**[*#†] (0.21) [0.27–0.33]	17.0	.01
	Coronal–apical	**0.14**[¶∫] (0.10) [0.12–0.15]	**0.12**[¶∫] (0.10) [0.10–0.14]	**0.11**[¶∫] (0.09) [0.10–0.13]	**0.20**[*§] (0.22) [0.15–0.19]	**0.17**[&§] (0.12) [0.16–0.19]	**0.18**[*§] (0.14) [0.17–0.20]	13.3	.01
Apex in mm	Δ3D	**0.33**[§∫] (0.24) [0.30–0.37]	**0.19** (0.13) [0.17–0.20]	**0.35**[§∫] (0.28) [0.31–0.39]	**0.36**[§∫] (0.25) [0.32–0.39]	**0.29**[§∫] (0.25) [0.25–0.32]	**0.73**[*#†] (0.55) [0.65–0.80]	67.1	.01
	Mesial–distal	**0.23**[#†∫] (0.18) [0.21–0.26]	**0.38**[*] (0.29) [0.34–0.42]	**0.25**[#†∫] (0.22) [0.21–0.28]	**0.32**[*] (0.23) [0.29–0.35]	**0.40**[*] (0.28) [0.36–0.44]	**0.42**[*] (0.29) [0.38–0.46]	19.4	.01
	Buccal–lingual	**0.39**[∫] (0.28) [0.35–0.43]	**0.40**[¶†∫] (0.29) [0.36–0.44]	**0.51**[#∫] (0.47) [0.44–0.58]	**0.30**[&†∫] (0.25) [0.26–0.34]	**0.31**[#∫] (0.23) [0.27–0.34]	**0.74**[*#†] (0.56) [0.66–0.82]	38.2	.01
	Coronal–apical	**0.13**[†∫] (0.09) [0.12–0.16]	**0.13**[†∫] (0.10) [0.11–0.14]	**0.11**[†∫] (0.08) [0.10–0.12]	**0.13**[†∫] (0.11) [0.12–0.15]	**0.17**[*#] (0.13) [0.16–0.19]	**0.17**[*#] (0.12) [0.15–0.18]	10.9	.01

*significant different ($p<.05$) to closed sleeve system.
#significant different ($p<.05$) to open sleeve system.
$significant different ($p<.05$) to H2 closed sleeve system.
&significant different ($p<.05$) to H4 closed sleeve system.
§significant different ($p<.05$) to H2 open sleeve system.
¶significant different ($p<.05$) to H4 open sleeve system.
†significant different ($p<.05$) to partially guided.
∫significant different ($p<.05$) to free hand placement.
S–Straumann Fully Guided Surgery System.
V–Versah Guided Surgery System.
Bold indicates statistically significant *p*-value of $p<.05$.

When using the surgical guide, the fit and stability of the guide is confirmed clinically; however, the inherent tolerances in the guide components are a potential source of error. Cassetta et al. looked specifically at the intrinsic error effects on the total error of fully guided surgery and to determine if limiting this tolerance can reduce the intrinsic error (Cassetta et al., 2013, 2015). This was completed by fabricating a metal shell, which attached to the head of the surgical handpiece and allowed for the direct attachment of the guide tubes of differing lengths. In turn, this minimized the amount of movement between the hand piece and the guide tube. The more guidance is, the lower the angular deviation. They showed that there is significant intrinsic error due to the mechanical components of the fully guided surgical systems, despite all the other clinical sources of error. The sleeve with the lateral window does allow for a higher degree of movement when the operator is not using the inner sleeve surface for guidance of the key. This potential source of error can be overcome when the keys are used in an ascending order for the initial drills that assures a continuous key-sleeve guidance and allows an accurate implant path preparation. Koop et al. showed that it is crucial to use the drill in a centric position, parallel to the sleeve for a minimal deviation during the implant bed preparation (Koop et al., 2013). They further suggested that longer drill keys and sleeves are critical for optimal accuracy. However, this can be a clinically challenging in posterior sites.

Oh et al. suggest that open sleeves might be advantageous in molar sites as they allow for smaller amount of mouth opening, making it possible to perform implant drilling in cases with an insufficient interarch space (Oh et al., 2021). In their in vitro study, they compared accuracy in terms of trueness of computer-assisted implant surgery placing each n=10 implants in typodonts using closed-form guides (with and without sleeves) with open-form guides (with and without sleeves) that had a C-shape and a lateral window buccally. The primary outcome parameter was the angular deviation in mesial–distal (MD) and buccal–lingual (BL) direction. The authors observed higher angular deviations in BL direction than in the MD direction for both, using a guide with an open sleeve (BL $3.52 \pm 2.76°$ versus MD $0.84 \pm 1.07°$) and for the guide with a closed sleeve (BL $1.49 \pm 1.46°$ vs MD $0.90 \pm 0.96°$) (Oh et al., 2021). These findings can be confirmed with the present results where a higher deviation in the buccal–lingual direction toward lingual was measured in comparison to the mesial–distal deviation. The angular deviation for the closed sleeve system appears to be comparable to the presented data ($1.35 \pm 0.64°$). However, the open sleeve system in this study resulted in clearly better data in respect to angular deviation ($1.49 \pm 0.69°$). Tallarico et al. reported a randomized clinical trial, where a combination of open and closed sleeves were used in placing implants n=16 utilizing surgical guides with lateral windows and n=33 implants using guides with closed sleeves (Tallarico et al., 2019). Using open sleeves resulted in $3.30 \pm 3.31°$ angular deviation and in the closed sleeve group, an angular deviation of $1.35 \pm 1.57°$ was observed. Oh et al. as well as Tallarico et al. simply removed the buccal circumference and used the same surgical kit with both, guides with open and closed sleeves. However, a surgical kit specifically designed to take advantage of a lateral window and long key-sleeve guidance (Versah) was used in this study, which may explain that there was no statistical difference between guides with open and closed sleeves. Which underlines the importance of selecting the best combination of sleeve/drill parameters in order to minimize probable errors in regards to angle deviation and deviations at the crest and apex of the implant (Apostolakis & Kourakis, 2018). The results of this study suggest that a long key-sleeve guidance is important for open sleeve systems.

The statistically calculated differences may not have in all circumstances clinical relevance. When interpreting the data, it should be considered how this translates clinically. A good example is given by Choi et al. who described that a one-degree angle deviation translates to 0.34-mm length deviation in the 10-mm fixture apical area. A 5-degree angle deviation translates to 1.7 mm length deviation. If the space between implant and tooth root were set to 1.5 mm during implant planning, a 5-degree angle error will impair the adjacent tooth root. Thus, the angle deviation should not exceed 3 degrees in order that the implant is installed safely without the tooth being damaged (Choi et al., 2004). In the presented study, only the fully guided groups using static surgical guides fulfilled these criteria, but the free-hand surgery and placement exceeded it. Computer-assisted implant surgery is therefore superior to free-hand implant placement, especially when there is proximity to critical anatomical structures.

The methods used in this study are not without inherent limitations. Inaccuracies have been investigated regarding the CBCT imaging techniques (Fokas et al., 2018), the digitization of the intraoral situation (Cho et al., 2015), the superimposition of dental situation and the CBCT (Han et al., 2021), and the fabrication of the surgical guide (Cassetta et al., 2013). Inaccuracies at each step of the digital workflow can individually and cumulatively affect the accuracy of computer-assisted implant surgery. Further limitations might be based on the methods for post-operative capturing of the actual implant position. However, using a completely digital registration appears to be as accurate as using a post-operative CBCT (Tang et al., 2019). Data interpretation may also depend on the study design to analyze the accuracy of the implant placement (Bover-Ramos et al., 2018). Bover-Ramos et al. compared the different study types (in vitro, clinical, or cadaver) and its impact on the accuracy data (Bover-Ramos et al., 2018). They showed that while approximately 1.6 times higher deviations were detected in clinical trials than in in vitro studies, the differences between the study types were not statistically significant. Future research investigating factors that influence the accuracy of implant placement should be extended to include technological and system-related factors, clinical factors, and operator experience.

5 | CONCLUSIONS

Within the limitations of this study, the following conclusions can be made:

- Computer-assisted implant surgery produced implant placement with higher trueness and precision compared with free-hand implant surgery.
- The closer the sleeve to the bone, the higher trueness and precision for both open and closed sleeve systems.
- No statistically significant difference in trueness was detected between the closed sleeve and the open sleeve with the lateral window, when the bone-sleeve distance was 2 and 4 mm.
- An increase in the bone-sleeve distance leads to a decrease of the precision, especially in the open sleeve system where the lateral window in the sleeve allows for a higher tolerance.
- While partially guided implant surgery using only the static guide for the pilot drill is significantly less true and precise than the fully guided approach with 2-mm sleeve-bone distance, it is still more

true and precise (not statistically significant but potentially clinically relevant) than the free-hand placement.

- The accuracy of the open sleeve system with a 4-mm bone-sleeve distance is statistically insignificant different from partially guided implant surgery.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Arndt Guentsch: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Visualization (lead); Writing – original draft (lead). **Hongseok An:** Formal analysis (supporting); Investigation (supporting); Validation (supporting); Visualization (supporting); Writing – review & editing (supporting). **Andrew R Dentino:** Conceptualization (supporting); Funding acquisition (supporting); Resources (equal); Supervision (lead); Writing – review & editing (supporting).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Apostolakis, D., & Kourakis, G. (2018). CAD/CAM implant surgical guides: maximum errors in implant positioning attributable to the properties of the metal sleeve/osteotomy drill combination. *International Journal of Implant Dentistry*, *4*(1), 34. https://doi.org/10.1186/s40729-018-0146-2

Bover-Ramos, F., Vina-Almunia, J., Cervera-Ballester, J., Penarrocha-Diago, M., & Garcia-Mira, B. (2018). Accuracy of implant placement with computer-guided surgery: A systematic review and meta-analysis comparing cadaver, clinical, and in vitro studies. *International Journal of Oral and Maxillofacial Implants*, *33*(1), 101–115. https://doi.org/10.11607/jomi.5556

Canullo, L., Tallarico, M., Radovanovic, S., Delibasic, B., Covani, U., & Rakic, M. (2016). Distinguishing predictive profiles for patient-based risk assessment and diagnostics of plaque induced, surgically and prosthetically triggered peri-implantitis. *Clinical Oral Implants Research*, *27*(10), 1243–1250. https://doi.org/10.1111/clr.12738

Cassetta, M., Di Mambro, A., Di Giorgio, G., Stefanelli, L. V., & Barbato, E. (2015). The influence of the tolerance between mechanical components on the accuracy of implants inserted with a stereolithographic surgical guide: A retrospective clinical study. *Clinical Implant Dentistry and Related Research*, *17*(3), 580–588. https://doi.org/10.1111/cid.12120

Cassetta, M., Di Mambro, A., Giansanti, M., Stefanelli, L. V., & Barbato, E. (2013). Is it possible to improve the accuracy of implants inserted with a stereolithographic surgical guide by reducing the tolerance between mechanical components? *International Journal of Oral and Maxillofacial Surgery*, *42*(7), 887–890. https://doi.org/10.1016/j.ijom.2013.01.011

Cassetta, M., Giansanti, M., Di Mambro, A., Calasso, S., & Barbato, E. (2013). Accuracy of two stereolithographic surgical templates: a retrospective study. *Clinical Implant Dentistry and Related Research*, *15*(3), 448–459. https://doi.org/10.1111/j.1708-8208.2011.00369.x

Cho, S. H., Schaefer, O., Thompson, G. A., & Guentsch, A. (2015). Comparison of accuracy and reproducibility of casts made by digital and conventional methods. *Journal of Prosthetic Dentistry*, *113*(4), 310–315. https://doi.org/10.1016/j.prosdent.2014.09.027

Choi, M., Romberg, E., & Driscoll, C. F. (2004). Effects of varied dimensions of surgical guides on implant angulations. *Journal of Prosthetic Dentistry*, *92*(5), 463–469. https://doi.org/10.1016/S002239130400527X

El Kholy, K., Janner, S. F. M., Schimmel, M., & Buser, D. (2019). The influence of guided sleeve height, drilling distance, and drilling key length on the accuracy of static Computer-Assisted Implant Surgery. *Clinical Implant Dentistry and Related Research*, *21*(1), 101–107. https://doi.org/10.1111/cid.12705

Ersoy, A. E., Turkyilmaz, I., Ozan, O., & McGlumphy, E. A. (2008). Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *Journal of Periodontology*, *79*(8), 1339–1345. https://doi.org/10.1902/jop.2008.080059

Evans, C. D., & Chen, S. T. (2008). Esthetic outcomes of immediate implant placements. *Clinical Oral Implants Research*, *19*(1), 73–80. https://doi.org/10.1111/j.1600-0501.2007.01413.x

Fokas, G., Vaughn, V. M., Scarfe, W. C., & Bornstein, M. M. (2018). Accuracy of linear measurements on CBCT images related to presurgical implant treatment planning: A systematic review. *Clinical Oral Implants Research*, *29*(Suppl 16), 393–415. https://doi.org/10.1111/clr.13142

Gargallo-Albiol, J., Barootchi, S., Marques-Guasch, J., & Wang, H. L. (2020). Fully guided versus half-guided and freehand implant placement: Systematic review and meta-analysis. *International Journal of Oral and Maxillofacial Implants*, *35*(6), 1159–1169. https://doi.org/10.11607/jomi.7942

Guentsch, A., Sukhtankar, L., An, H., & Luepke, P. G. (2021). Precision and trueness of implant placement with and without static surgical guides: An in vitro study. *Journal of Prosthetic Dentistry*, *126*, 398–404. https://doi.org/10.1016/j.prosdent.2020.06.015

Hämmerle, C. H. F., & Tarnow, D. (2018). The etiology of hard- and soft-tissue deficiencies at dental implants: A narrative review. *Journal of Clinical Periodontology*, *45*(Suppl 20), S267–S277. https://doi.org/10.1111/jcpe.12955

Han, Y.-T., Lin, W.-C., Fan, F.-Y., Chen, C.-L., Lin, C.-C., & Cheng, H.-C. (2021). Comparison of dental surface image registration and fiducial marker registration: an in vivo accuracy study of static computer-assisted implant surgery. *Journal of Clinical Medicine*, *10*(18), 4183. https://doi.org/10.3390/jcm10184183

ISO-5725-1:1994(E). (2018). *Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions*. Geneva: International Organization for Standardization. ISO Store Order: OP-449776 (Date: 2020-06-18). http://www.iso.org/iso/home.html

Jung, R. E., Schneider, D., Ganeles, J., Wismeijer, D., Zwahlen, M., Hammerle, C. H., & Tahmaseb, A. (2009). Computer technology applications in surgical implant dentistry: A systematic review.

International Journal of Oral and Maxillofacial Implants, *24*(Suppl), 92–109. https://www.ncbi.nlm.nih.gov/pubmed/19885437

Kessler, A., Le, V., & Folwaczny, M. (2021). Influence of the tooth position, guided sleeve height, supporting length, manufacturing methods, and resin E-modulus on the in vitro accuracy of surgical implant guides in a free-end situation. *Clinical Oral Implants Research*, *32*(9), 1097–1104. https://doi.org/10.1111/clr.13804

Koop, R., Vercruyssen, M., Vermeulen, K., & Quirynen, M. (2013). Tolerance within the sleeve inserts of different surgical guides for guided implant surgery. *Clinical Oral Implants Research*, *24*(6), 630–634. https://doi.org/10.1111/j.1600-0501.2012.02436.x

Naziri, E., Schramm, A., & Wilde, F. (2016). Accuracy of computer-assisted implant placement with insertion templates. *GMS Interdisciplinary Plastic and Reconstructive Surgery DGPW*, *5*, Doc15. https://doi.org/10.3205/iprs000094

Oh, K. C., Shim, J. S., & Park, J. M. (2021). In vitro comparison between metal sleeve-free and metal sleeve-incorporated 3d-printed computer-assisted implant surgical guides. *Materials (Basel)*, *14*(3), 615. https://doi.org/10.3390/ma14030615

Park, C., Raigrodski, A. J., Rosen, J., Spiekerman, C., & London, R. M. (2009). Accuracy of implant placement using precision surgical guides with varying occlusogingival heights: an in vitro study. *Journal of Prosthetic Dentistry*, *101*(6), 372–381. https://doi.org/10.1016/S0022-3913(09)60080-9

Salomo-Coll, O., Auriol-Muerza, B., Lozano-Carrascal, N., Hernandez-Alfaro, F., Wang, H. L., & Gargallo-Albiol, J. (2021). Influence of bone density, drill diameter, drilling speed, and irrigation on temperature changes during implant osteotomies: An in vitro study. *Clinical Oral Investigations*, *25*(3), 1047–1053. https://doi.org/10.1007/s00784-020-03398-y

Schnutenhaus, S., Edelmann, C., Rudolph, H., Dreyhaupt, J., & Luthardt, R. G. (2018). 3D accuracy of implant positions in template-guided implant placement as a function of the remaining teeth and the surgical procedure: A retrospective study. *Clinical Oral Investigations*, *22*(6), 2363–2372. https://doi.org/10.1007/s00784-018-2339-8

Tahmaseb, A., Wu, V., Wismeijer, D., Coucke, W., & Evans, C. (2018). The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clinical Oral Implants Research*, *29*(Suppl 16), 416–435. https://doi.org/10.1111/clr.13346

Tallarico, M., Martinolli, M., Kim, Y., Cocchi, F., Meloni, S. M., Alushi, A., & Xhanari, E. (2019). Accuracy of computer-assisted template-based implant placement using two different surgical templates designed with or without metallic sleeves: a randomized controlled trial. *Dent J (Basel)*, *7*(2), 41. https://doi.org/10.3390/dj7020041

Tang, T., Liao, L., Huang, Z., Gu, X., & Zhang, X. (2019). Accuracy of the evaluation of implant position using a completely digital registration method compared with a radiographic method. *Journal of Prosthetic Dentistry*, *122*(6), 537–542. https://doi.org/10.1016/j.prosdent.2018.11.020

Tatakis, D., Chien, H., & Parashis, A. (2019). Guided implant surgery risks and their prevention. *Periodontology 2000*, *2000*(81), 194–208. https://doi.org/10.1111/prd.12292

Tattan, M., Chambrone, L., Gonzalez-Martin, O., & Avila-Ortiz, G. (2020). Static computer-aided, partially guided, and free-handed implant placement: A systematic review and meta-analysis of randomized controlled trials. *Clinical Oral Implants Research*, *31*(10), 889–916. https://doi.org/10.1111/clr.13635

Van Assche, N., Vercruyssen, M., Coucke, W., Teughels, W., Jacobs, R., & Quirynen, M. (2012). Accuracy of computer-aided implant placement. *Clinical Oral Implants Research*, *23*(Suppl 6), 112–123. https://doi.org/10.1111/j.1600-0501.2012.02552.x

Vasak, C., Watzak, G., Gahleitner, A., Strbac, G., Schemper, M., & Zechner, W. (2011). Computed tomography-based evaluation of template (NobelGuide)-guided implant positions: a prospective radiological study. *Clinical Oral Implants Research*, *22*(10), 1157–1163. https://doi.org/10.1111/j.1600-0501.2010.02070.x

Vercruyssen, M., Fortin, T., Widmann, G., Jacobs, R., & Quirynen, M. (2014). Different techniques of static/dynamic guided implant surgery: Modalities and indications. *Periodontology 2000*, *66*(1), 214–227. https://doi.org/10.1111/prd.12056

Vercruyssen, M., Hultin, M., Van Assche, N., Svensson, K., Naert, I., & Quirynen, M. (2014). Guided surgery: Accuracy and efficacy. *Periodontology 2000*, *66*(1), 228–246. https://doi.org/10.1111/prd.12046

Widmann, G., & Bale, R. J. (2006). Accuracy in computer-aided implant surgery - a review. *International Journal of Oral and Maxillofacial Implants*, *21*, 305–313.

Younes, F., Cosyn, J., De Bruyckere, T., Cleymaet, R., Bouckaert, E., & Eghbali, A. (2018). 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*, *45*(6), 721–732. https://doi.org/10.1111/jcpe.12897

Zhou, W., Liu, Z., Song, L., Kuo, C. L., & Shafer, D. M. (2018). Clinical factors affecting the accuracy of guided implant surgery-a systematic review and meta-analysis. *Journal of Evidence Based Dental Practice*, *18*(1), 28–40. https://doi.org/10.1016/j.jebdp.2017.07.007

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