Tufts UNIVERSITY | School of Dental Medicine

Accuracy of Different Surgical Guide Designs for Static Computer-Assisted Implant Surgery: An in vitro Study

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ABSTRACT

Aims & Hypothesis: The aims of this study were to evaluate the effect of (i) different surgical guide designs and (ii) implant placement location in the accuracy of guided implant placement in single edentulous site using an in vitro study model. The null hypothesis proposed was that there is no difference in accuracy in different location and using different designs of implant surgical guide.

Materials & Methods: Thirty partially edentulous typodonts were labeled, scanned, and divided into two groups: Group 1 – full-arch surgical guide and Group 2 – shortened surgical guide. Acquired STL files were imported into implant planning software. Virtual implant planning and designing of surgical guide were performed. All surgical guides were printed and used for guided implant placement on all typodonts. Scanbodies were placed on all typodonts and post-op STL files were obtained. Superimposition of pre-op and post-op STL files were performed and the accuracy of implant position was evaluated.

Results: For the angular deviation, the interaction was not statistically significant between group and implant ($p=0.276$). The main effect for group was not statistically significant ($p=0.892$). The main effect for implant location was statistically significant ($p<0.001$), with implant #7 demonstrating significantly higher deviation than implant #9 ($p=0.001$) and implant #14 ($p=0.001$). For 3D offset at base, the interaction was statistically significant between group and implant ($p=0.002$). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 ($p=0.001$), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant ($p=0.503$). Within group 2, the difference between implants was statistically significant ($p<0.001$), with implant #4 demonstrating significantly higher deviation than implant #9 (p<0.001) and implant #14 (p=0.0079) and implant #7 demonstrating significantly higher deviation than implant #9 (p=0.001). For the 3D offset at tip, the interaction was statistically significant between groups and implants (p=0.031). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 (p=0.015), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant (p=0.377). Within group 2, the difference between implants was statistically significant (p<0.001), with implant #4 demonstrating significantly higher deviation than implant #9 (p<0.001) and implant #7 demonstrating significantly higher deviation than implant #9 (p=0.001).

Conclusions: Despite the limitations of this in-vitro study, the results demonstrated for one single-tooth or two single-tooth edentulous site, fully guided implant surgery using shortened surgical guide presented higher accuracy compared to full-arch surgical guide.

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LIST OF ABBREVIATIONS

Cone beam computed tomography = CBCT

Static computer-assisted implant surgery = sCAIS

Standard tessellation language = STL

Digital imaging and communications in medicine = DICOM

Full-arch surgical guide = FASG

Shortened surgical guides = SSG

Digital light processing = DLP

Stereolithography apparatus = SLA

Fused filament fabrication = FFF

Standard deviation = SD

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Accuracy of different surgical guide designs for static Computer-Assisted Implant Surgery: An in vitro study

In modern dentistry, implant therapy has been proven to be a promising treatment modality for edentulous and partially edentulous patients since it was first developed by Dr. Brånemark. In the field of implant dentistry, implant position is one of the most critical factors for long-term success.[1-4] In general, misplaced implants are not only more difficult to be restored but also more susceptible to biological (e.g. peri-implantitis) or technical (e.g. screw loosening) complications.[5,6] When it comes to challenging surgical site with limited bone presented or anterior aesthetic zone, reliable tools which can help position implants precisely should be utilized. Recently, digital technology has been introduced to increase the accuracy and facilitate treatment rendered. Please see *Figure 1* for workflow from virtual planning to physical guided surgery.

Data collection such as digital impression and acquisition of CBCT first took place. Digital impression (or intra-oral surface scanning) seemed to have comparable accuracy as conventional impression.[7,8] Virtual implant planning using CBCT image with intra-oral surface scanning has been used for static computer-assisted implant surgery (sCAIS). The outcomes of this procedure seem to secure the tentative implant position and therefore achieve more promising outcomes.[9-12] Virtual implant planning allows the clinician to visualize anatomical structures in three-dimensional aspects and relate the alveolar structures with prosthetically ideal implant position. The alignment of surface scans, including the prosthetic planning, with 3D volumetric imaging data (CBCT) is recommended to improve the accuracy of the ideal implant position. Surgical guides should be digitally designed on surface scan files (STL file) which have been aligned with DICOM data, which is more accurate than using DICOM data alone.[12] Furthermore, superimposing the DICOM file from CBCT image with STL file from intraoral or model scan with a digitalized wax-up, the final implant prosthesis can be visualized and be predicted before implant was placed.[13,14] A surgical guide can also be designed in the software and then be fabricated by, most commonly, 3D printers or milling machines. Even though sCAIS is more accurate than free-hand implant placement,[15] several limitations are still present.

The final implant location compared to initially planned position using sCAIS is dictated by a sum of errors from data acquisition, implants planning, surgical guide fabrications and actual implant placement procedure.[16,17] Therefore, identifying the source of error is important to increase the predictability of static guided implant surgery.[12] A recent ITI (International Team for Implantology) consensus report based on several systematic reviews concluded that there is still a lack of evidence in the literature investigating the source of deviations in every step of the sCAIS.[18] The authors suggested that the factors within the digital workflow contributing to deviations in the actual implant position from the initial planned position should be investigated individually.

The accuracy of final implant position can be evaluated with three major aspects. Angular deviation may affect the design of final implant prosthesis. For example, if a screw-retained implant fixed partial denture was planned, when large angular deviation presented after implant placed, the design of custom-abutment and cement-retained fixed partial denture may have to be considered as an alternative option; or an angled screw-retained abutment may need to be used. 3D offset at base is important when the implant site is tight mesio-distally on coronal level or at anterior aesthetic zone. Large 3D offset at base may cause issues for pathway of insertion; ridge lap can also be presented, causing unpleasant aesthetic outcome of final prosthesis or insufficient cleansability for patients. 3D offset at tip of implants is extremely important when the root of adjacent tooth is tilted toward the implant site or when the planned implant position is close to inferior alveolar nerve canal.

Regarding the different supports for surgical guide, three major designs are presented: tooth-borne guides, mucosa-borne guides, and tooth-mucosa-borne guides. Tooth-borne guides are designed for partially edentulous ridges while mucosa-borne guides are designed for fully edentulous ridge and tooth-mucosa-borne guides are normally designed for distally edentulous ridges. Different opinions were proposed by previous studies investigating the accuracy between three major designs.[9-11] To date, there is still no clear guideline regarding surgical guide design for sCAIS and the predictability of guided implant surgery in different locations.

Within tooth-borne guides, full arch guides are usually designed by default since more abutment teeth seem to provide better stability. However, there is still lack of evidence in the literature indicating that shortened surgical guides are not as accurate as full arch guides. If shorten guides can be proven to have similar accuracy as full arch guides, clinicians will benefit from several aspects such as decrease in fabrication time and cost.

Aim and Hypothesis

The aims of this study were to evaluate the effect of (i) different surgical guide designs and (ii) implant placement location in the accuracy of guided implant placement in single edentulous sites.

Primary outcome:

The primary outcome of this study was the accuracy of the final implant position measured in millimeter and angular deviation in degree.

Null hypothesis:

The null hypothesis of this study was that in fully guided implant surgery there is no difference in the final implant position using different surgical guide designs and implant location.

Materials and Methods

Thirty partially edentulous acrylic typodonts (Partially Edentulous Drillable Maxilla, Models Plus LLC) with missing teeth #4, #7, #9 and #14 were used, as demonstrated in *Figure 2.* All thirty typodonts were labeled and scanned with an intraoral scanner (TRIOS 3, 3-Shape, Copenhagen, Denmark); acquired STL files were imported into implant planning software (CoDiagnostiX, Dentalwings, Montreal, Canada). Virtual implant planning and virtual designing of surgical guide were performed on CoDiagnostiX. All surgical guides were printed with a 3D printer (Varseo 3D printing system, BEGO, Germany) and fitting was checked. Guided implant placement was performed. Scanbodies were placed on all typodonts and all typodonts were scanned with a lab scanner (CARES 7 lab scanner, Dentalwings, Montreal, Canada). Acquired STL files were imported into CoDiagnostiX. Superimposition of pre-op and post-op STL files was performed and accuracy evaluation was performed on CoDiagnostiX. See study workflow in *Figure 3*.

Study Groups

The 30 typodonts were equally divided into two groups (15 for each group). For Group 1, a full-arch surgical guide (FASG) was designed individually for every typodont. For Group 2, three different shortened surgical guides (SSG) were designed on each typodont. For subgroup 2a, guides were designed on abutment tooth #2, #3, #6 and #8; for subgroup 2b, guides were designed on abutment tooth #8, #10, #11 and #12 and for subgroup 2c, guides were designed on abutment tooth #10, #11, #12, and #15. See *Figure 4*.

Pre-op Cast Scanner

All 30 typodonts were scanned with a high-resolution intra-oral scanner (TRIOS 3, 3-Shape, Copenhagen, Denmark) by the same operator (YW). The intra-oral scanner resolution according to the manufacturer are 6.9 ± 0.9 µm for trueness (accuracy) and 4.5 ± 0.9 µm for precision (consistency).[19]

Virtual Implant Planning

The obtained STL files were imported into the computer planning software (CoDiagnostiX, Dentalwings, Montreal, Canada). Imported STL files were performed individually for each sample. At the mesio-distal aspect the implants were positioned centrally, bucco-lingually the implants were positioned in the central fossa and apico-coronally the implants were positioned 2 mm apical to the proposed mucosal margin. Bone Level Tapered Regular Crossfit 4.1 x 10 mm (Straumann AG, Basel, Switzerland) implants were planned for all four different sites. All implant planning was performed by the same operator (YW) under supervision of the principal investigator (ADS).

Surgical Guide Design and Fabrication

All surgical guides were designed on the same software (coDiagnostiX, Dentalwings, Montreal, Canada) based on the established implant planned position. A cylindrical sleeve 5 mm diameter and length were used for all implants. The sleeve position was established at 6 mm from the implant shoulder (H6). Therefore, all the guided drills and handle length were the same. A total of 60 surgical guides were designed (15 FASG and 45 SSG) corresponding to the specific implant location. The FASG comprised all abutment teeth and SSG comprised four abutment teeth. The offset to set the clearance between surgical guide and the teeth contact surface was established at 15 µm. The surgical guide wall thickness was established at 3 mm. Inspection windows on tooth #3 #6 #8 #11 were placed correspondingly to check surgical guide seating (*Figure 5*). All surgical guides were printed in polyurethane using the same printing machine (Varseo S, BEGO, Germany), which utilizes DLP technology and is reported to have 25 µm of resolution according to the manufacturer.[20] All surgical guides were designed by the same operator (YW) under supervision of the principal investigator (ADS).

Guided Implant Placement

After metal sleeves were secured on all surgical guides, guided implant placement was performed following the sequential drilling osteotomies according to the manufacturer. The type of implant used in the study was Straumann Bone Level Tapered Regular Crossfit 4.1 x 10 mm (Straumann AG, Basel, Switzerland). A total of 120 implants were placed on #4 #7 #9 #14 position on all 30 typodonts. For Group 1, FASG was used to place all four implants. For Group 2, SSG 2a was used to place implants #4 and #7, SSG 2b was used to place implant #9 and SSG 2c was used to place implant #14. All implants were placed by the same operator (YW) under supervision of the principal investigator (ADS).

The drilling protocol is demonstrated as below:

1. Mucosa Punch, guided, length 30 mm, Ø 4.7 mm with 800 rpm
2. Milling Cutter, guided, length 32.5 mm, Ø 3.5 mm with 1200 rpm
3. BLT Pilot Drill, long, guided, length 41.4 mm, Ø 2.2 mm with 1200 rpm

4. BLT Drill, long, guided, length 41.4 mm, ∅ 2.8 mm with 1200 rpm
5. BLT Drill, long, guided, length 41.4 mm, ∅ 3.5 mm with 1200 rpm
6. BLT Profile Drill, guided, length 36 mm, ∅ 4.1 mm with 800 rpm
7. BLT Tap, guided, length 42 mm, ∅ 4.1 mm with 60 N.cm
8. Implant insertion with 60 N.cm.
    - Mount on implant was removed after each implant was placed in order to eliminate influence on other implant placement. Hand-torque with ratchet was utilized if implants did not reach to the tentative planned depth.

※ Handles were used correspondingly.

Accuracy Evaluation

After implant placement, scanbodies (CARES® RC Mono Scanbody, D 4.8 mm, H 10 mm, PEEK, Straumann, Basel, Switzerland) were screwed on all typodonts with 15 N.cm (*Figure 6*) and new cast scans were taken (CARES 7 lab scanner with accuracy of 15 µm, Dentalwings, Montreal, Canada) producing post-op STL files. These files were imported at previous digital plan on implant planning software (coDiagnostiX, Dentalwings, Montreal, Canada). Superimposition of the scanned STL files and the virtual planning STL files were performed using fixed landmarks (Tooth #2 #6 #8 #11 #15) (*Figure 7*). Accuracy of all superimposed images was checked. Data from 120 implants on all 30 typodonts were collected. Angular deviation, 3D offset (base and tip), mesial-distal (base and tip), buccal-lingual (base and tip) and apical-coronal (base and tip) deviation were measured. Angle deviation was measured in degrees and offset was measured in mm. Note that the term “base” refers to the platform of the implant and “tip” refers to the apex of the implant. *Figure 8* demonstrates how samples were measured.

Statistical Analysis

Descriptive statistics (means, standard deviations, minima, and maxima) were calculated by group and subgroup. Comparisons between the groups and subgroups were conducted via two-way mixed ANOVA; post-hoc testing for subgroups used the Bonferroni correction ($\alpha = 0.0083$). In the case of a non-significant interaction, the main effects of group and implant were examined. On the other hand, in the case of a significant interaction, simple main effects were examined (the implants were compared for each group, and the groups were compared for each implant). Quantile-quantile plots were used to assess the assumption of normality, and Levene's test was used to assess the assumption of homogeneity of variances. The level of significance was established at $\alpha = 0.05$ with the exception of tests using the Bonferroni correction. A separate analysis was performed for nine outcomes (angular deviation, 3D off set at base and tip, mesial-distal at base and tip, buccal-lingual at base and tip, and apical-coronal at base and tip). SPSS version 26 was used in the analysis.

Results

Angular Deviation

Table 1 displays descriptive statistics for angular deviation by group and subgroup. In each group, the highest mean was obtained in implant #7. The interaction was not statistically significant between group and implant (p=0.276). The main effect for group was not statistically significant (p=0.892). The main effect for implant was statistically significant (p<0.001). In post-hoc tests, the mean for implant #7 was significantly higher than that of implant #9 (p=0.001) and implant #14 (p=0.001). The other post-hoc tests were not significant.

3D Offset at Base

Table 2 displays descriptive statistics for 3D offset at base by group and subgroup. The interaction was statistically significant between group and implant (p=0.002). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 (p=0.001), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant (p=0.503). Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests within group 2, the mean for implant #4 was significantly higher than that of implant #9 (p<0.001) and implant #14 (p=0.0079). In addition, the mean for implant #7 was significantly higher than that of implant #9 (p=0.001). The other post-hoc tests were not significant.

Mesial-Distal Offset at Base

Table 3 displays descriptive statistics for mesial-distal offset at base by group and subgroup. The interaction was statistically significant between group and implant ($p=0.037$). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 ($p=0.011$), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant ($p=0.531$). Within group 2, the difference between implants was statistically significant ($p<0.001$). In post-hoc tests within group 2, the mean for implant #4 was significantly higher than that of implant #9 ($p<0.001$) and implant #14 ($p=0.002$). In addition, the mean for implant #7 was significantly higher than that of implant #9 ($p=0.002$). The other post-hoc tests were not significant.

Buccal-lingual Offset at Base

Table 4 displays descriptive statistics for buccal-lingual offset at base by group and subgroup. The interaction was not statistically significant between group and implant ($p=0.076$). The main effect for implant was not statistically significant ($p=0.665$). The main effect for group was not statistically significant ($p=0.684$).

Apical-Coronal Offset at Base

Table 5 displays descriptive statistics for apical-coronal offset at base by group and subgroup. The interaction was statistically significant between group and implant ($p=0.040$). Analysis of simple main effects showed that the only significant difference between groups was for implant #14 ($p=0.023$), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant ($p=0.439$).

Within group 2, the difference between implants was statistically significant (p=0.046); however, none of the post-hoc tests was statistically significant when applying the Bonferroni correction.

3D Offset at Tip

Table 6 displays descriptive statistics for 3D offset at tip by group and subgroup. The interaction was statistically significant between group and implant (p=0.031). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 (p=0.015), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant (p=0.377). Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests within group 2, the mean for implant #4 was significantly higher than that of implant #9 (p<0.001). In addition, the mean for implant #7 was significantly higher than that of implant #9 (p=0.001). The other post-hoc tests were not significant.

Mesial-Distal Offset at Tip

Table 7 displays descriptive statistics for mesial-distal offset at tip by group and subgroup. The interaction was statistically significant between group and implant (p=0.045). Analysis of simple main effects showed that the only significant difference between groups was for implant #9 (p=0.025), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant (p=0.274). Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests within group 2, the mean for implant #4 was significantly higher than that of implant #9 (p<0.001) and implant #14 (p=0.004). In addition, the mean for implant #7 was significantly higher than that of implant #9 (p=0.001). The other post-hoc tests were not significant.

Buccal-Lingual Offset at Tip

Table 8 displays descriptive statistics for buccal-lingual offset at tip by group and subgroup. The interaction was not statistically significant between group and implant (p=0.051). The main effect for implant was not statistically significant (p=0.395). The main effect for group was not statistically significant (p=0.151).

Apical-Coronal Offset at Tip

Table 9 displays descriptive statistics for apical-coronal offset at tip by group and subgroup. The interaction was statistically significant between group and implant (p=0.040). Analysis of simple main effects showed that the only significant difference between groups was for implant #14 (p=0.022), with group 1 exhibiting a higher mean for this implant. Within group 1, the difference between implants was not statistically significant (p=0.512). Within group 2, the difference between implants was statistically significant (p=0.021). In post-hoc tests within group 2, the mean for implant #4 was significantly higher than that of implant #14 (p=0.007). The other post-hoc tests were not significant.

Discussion

When investigating the effect of group, no significant difference was found for angular deviation. However, significant differences were found for 3D offset at base and 3D offset at tip, with SSG (Group 2) demonstrating better accuracy for implant #9 compared to FASG (Group 1). This finding could be caused by bending effect or distortion since the position is located at the center of FASG.

The main effect of implant location was significant for angular deviation; significantly higher deviation was found for implant #7 than for implant #9 and implant #14. Within Group 1, no significant difference was found between different implant locations for 3D offset at base and 3D offset at tip; within Group 2, implant #4 and implant #7 demonstrated significantly higher deviation than implant #9 and implant #14 for 3D offset at base and 3D offset at tip. Therefore, in Group 2 (SSG on four abutment teeth), guides designed for one single-tooth edentulous surgical site appeared to be more accurate than guides designed for two single-tooth edentulous surgical sites.

Even though sCAIS has presented higher accuracy compared to free-hand implant placement,[21,22] several factors can potentially influence its accuracy. The accuracy of guided implant surgery is a sum of errors within the digital workflow process, from data acquisition to surgical guide printing. In addition, the factors related to site or patient could also influence the accuracy. In general, the deviation generated for each group in this study can be the result of: (i) accuracy of intra-oral scanners and lab scanner; (ii) errors from the 3D printer; (iii) offset and bending effect of surgical guides; (iv) height of metal sleeves and thickness of soft tissue; (v) design of the implant; and (vi) clinician expertise.

Accuracy of Digital Impression

Although digital impressions have demonstrated comparable accuracy to conventional impressions,[7,8] Ender et al. found that shorten-arch digital impressions demonstrated higher accuracy than full-arch digital impressions.[23] In the case of shorten edentulous surgical site, a shorten-arch digital impression can be used to improve the accuracy of digital impression. The results of the Ender et al. study could also justify higher discrepancy found in the present study when full-arch surgical guides were used.

Different 3D Printers

Different types of 3D dental printers are available on the market. Out of all technology, stereolithography apparatus (SLA), digital light processing (DLP), fused filament fabrication (FFF), and the PolyJet were commonly used. The PolyJet and DLP techniques were more precise than the FFF and SLA techniques, with the PolyJet technique having the highest accuracy.[24] However, there is still a lack of evidence in the literature demonstrating a superiority of one printer over another in regards to the final implant position compared to the initial planned.

Offset between Surgical Guide and Surface Scan and Bending Effect of Surgical Guides

The offset between surgical guide and intra-oral surface scan is mandatory for digitally designed surgical guides to compensate errors from data acquisition and/or impression. A longer surgical guide tends to bend easier when force is applied. However, there is no sufficient evidence mentioning about the bending effect on surgical guides. It should be also emphasized that different printing materials have different levels of rigidity, which could also influence the bending effect.

Effect of Metal Sleeves Height

For sCAIS a closer distance between metal sleeve and the implant shoulder seems to make implant placement more accurate. Kholy et al. found that decreasing the drilling distance below the guided sleeve by using shorter sleeve heights or shorter implants can significantly increase the accuracy of sCAIS.[25] However, there is no clinical study confirming the results and more studies are necessary. In this study a distance between sleeves to implant shoulder was 6 mm; the use of this distance was set based on the study design using flapless implant surgery, which requires more space.

Implant Macrodesign

Implant macrodesign seemes to have an effect on the guided implant placement protocol. Kholy et al. found that tapered implants demonstrated slightly better positional accuracy than parallel-walled implants.[26]

Expertise

It was believed that guided implant surgery would not require a higher level of surgical experience in order to obtain predictable outcomes. However, a recently published article by Marei et al. demonstrated that the level of surgeon's expertise could significantly affect the accuracy of guided implant surgery.[27] The study showed that in the buccolingual direction, the expert surgeons performed more accurate implant placement (3.7 ± 3.35 mm) compared with the novice surgeons (8.5 ± 6.3 mm).

Agreement and Disagreement with Previous Studies

The effects of full arch, 4-teeth, 3-teeth, or 2-teeth supported Static 3D printed surgical guides were recently compared in another in vitro study.[28] Acrylic bone models were used, and each study model included three single-tooth gap situations: one extraction socket site and two implants placed in a distal extension situation. All models were scanned and digital treatment planning including correct 3D implant positioning was performed. Surgical guides were designed and produced, with standardized design, production variables and material. Preplanned and postoperative implant positions were compared in 3-dimensional aspects and angular deviations. The authors found significantly more deviation for surgical guides using 3-teeth or 2-teeth compared to 4-teeth or full-arch. However, they did not find a statistically significant difference between 4-teeth and full-arch surgical guide. These results are in disagreement with the results of our study, where FASG seemed to present higher 3D deviation compared to SSG, which also used 4 teeth supporting surgical guide. There are, however, some differences between the current study and the Kholy et al. study, such as: (i) type of surgery (flap versus flapless); (ii) 3D printer used; (iii) implant macrodesign and (iv) post-op scanning.

Limitations

This study presents several limitations such as: (i) the acrylic typodont could generate different outcomes compared to alveolar bone; (ii) only two surgical guide designs were compared; (iii) the sleeve position was established at 6 mm from the implant shoulder due to the thickness of soft tissue; (iv) flapless surgery was performed; it seems that flapless surgery could produce more errors than open-flap surgery.[29]

Conclusion

Despite the limitations of this in-vitro study, conclusions can be drawn that with one single-tooth or two single-tooth edentulous site, fully guided implant surgery using shortened surgical guide presented higher accuracy compared to full-arch surgical guide. Further research on different patterns of partially edentulous ridges, different designs of surgical guides or different implants designs should be investigated to provide more information for clinicians to design reliable surgical guides in a more cost-effective manner.

APPENDICES

Appendix A: Tables

Appendix B: Figures

Appendix A: Tables

Table 1. Descriptive Analysis for Angle Deviation (in degrees; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	3.00	1.68	0.3	6.3
	7	3.35	1.28	1.2	5.1
	9	2.79	1.62	1.1	5.9
	14	2.51	1.33	0.8	5.4
2	4	3.27	1.09	1.0	5.0
	7	3.79	1.40	1.4	7.2
	9	2.19	0.73	0.9	3.7
	14	2.23	1.34	0.3	5.2

The interaction was not statistically significant between group and implant (p=0.276).

The difference between implants was statistically significant (p<0.001); in post-hoc tests, the difference between implant #7 and implant #9 was significant (p=0.001), and the difference between implant #7 and implant #14 was significant (p=0.001).

The difference between groups was not statistically significant (p=0.892).

Table 2. Descriptive Analysis for 3D Offset at Base (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.60	0.23	0.30	1.08
	7	0.66	0.14	0.36	0.89
	9	0.67	0.19	0.35	0.93
	14	0.60	0.27	0.20	1.21
2	4	0.66	0.20	0.31	1.03
	7	0.66	0.22	0.33	1.18
	9	0.43	0.18	0.09	0.85
	14	0.46	0.16	0.25	0.83

The interaction was statistically significant between group and implant (p=0.002).

For implant #9, the difference between group 1 and group 2 was statistically significant (p=0.001).

Within group 1, the difference between implants was not statistically significant (p=0.503).

Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests, the difference between implant #4 and implant #9 was significant (p<0.001), the difference between implant #4 and implant #14 was significant (p=0.0079), and the difference between implant #7 and implant #9 was significant (p=0.001).

Table 3. Descriptive Analysis for Mesial-Distal Offset at Base (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.41	0.23	0.07	0.84
	7	0.43	0.23	0.04	0.74
	9	0.39	0.22	0.03	0.75
	14	0.33	0.22	0.09	0.78
2	4	0.48	0.18	0.18	0.73
	7	0.42	0.15	0.14	0.69
	9	0.20	0.15	0.02	0.32
	14	0.24	0.18	0.01	0.67

The interaction was statistically significant between group and implant (p=0.037).

For implant #9, the difference between group 1 and group 2 was statistically significant (p=0.011).

Within group 1, the difference between implants was not statistically significant (p=0.531).

Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests, the difference between implant #4 and implant #9 was significant (p<0.001), the difference between implant #4 and implant #14 was significant (p=0.002), and the difference between implant #7 and implant #9 was significant (p=0.002).

Table 4. Descriptive Analysis for Buccal-lingual Offset at Base (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.24	0.25	0.02	0.82
	7	0.24	0.16	0.07	0.56
	9	0.33	0.20	0.01	0.66
	14	0.27	0.24	0.00	0.74
2	4	0.29	0.19	0.06	0.61
	7	0.39	0.24	0.02	0.95
	9	0.22	0.17	0.01	0.41
	14	0.25	0.20	0.02	0.61

The interaction was not statistically significant between group and implant (p=0.076).

The difference between implants was not statistically significant (p=0.665).

The difference between group 1 and group 2 was not statistically significant (p=0.684).

Table 5. Descriptive Analysis for Apical-Coronal Offset at Base (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.26	0.12	0.04	0.42
	7	0.33	0.17	0.06	0.61
	9	0.32	0.21	0.03	0.79
	14	0.33	0.19	0.06	0.63
2	4	0.29	0.14	0.03	0.51
	7	0.26	0.14	0.03	0.49
	9	0.21	0.17	0.01	0.58
	14	0.18	0.13	0.02	0.37

The interaction was statistically significant between group and implant (p=0.040).

For implant #14, the difference between group 1 and group 2 was statistically significant (p=0.023).

Within group 1, the difference between implants was not statistically significant (p=0.439).

Within group 2, the difference between implants was statistically significant (p=0.046); however, none of the post-hoc tests was statistically significant when applying the Bonferroni correction.

Table 6. Descriptive Analysis for 3D Offset at Tip (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	1.06	0.55	0.17	2.14
	7	1.19	0.33	0.48	1.66
	9	1.11	0.44	0.59	1.78
	14	0.97	0.44	0.46	1.83
2	4	1.19	0.38	0.52	1.81
	7	1.29	0.47	0.55	2.42
	9	0.76	0.28	0.31	1.39
	14	0.81	0.40	0.25	1.72

The interaction was statistically significant between group and implant (p=0.031).

For implant #9, the difference between group 1 and group 2 was statistically significant (p=0.015).

Within group 1, the difference between implants was not statistically significant (p=0.377).

Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests, the difference between implant #4 and implant #9 was significant (p<0.001), and the difference between implant #7 and implant #9 was significant (p=0.001).

Table 7. Descriptive Analysis for Mesial-Distal Offset at Tip (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.79	0.48	0.01	1.60
	7	0.93	0.51	0.03	1.63
	9	0.74	0.50	0.06	1.51
	14	0.66	0.44	0.03	1.68
2	4	0.93	0.35	0.35	1.48
	7	0.85	0.33	0.30	1.51
	9	0.39	0.30	0.03	1.20
	14	0.48	0.35	0.07	1.42

The interaction was statistically significant between group and implant (p=0.045).

For implant #9, the difference between group 1 and group 2 of was statistically significant (p=0.025).

Within group 1, the difference between implants was not statistically significant (p=0.274).

Within group 2, the difference between implants was statistically significant (p<0.001). In post-hoc tests, the difference between implant #4 and implant #9 was significant (p<0.001), the difference between implant #4 and implant #14 was significant (p=0.004), and the difference between implant #7 and implant #9 was significant (p=0.001).

Table 8. Descriptive Analysis for Buccal-Lingual Offset at Tip (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.48	0.51	0.00	1.61
	7	0.44	0.31	0.03	1.20
	9	0.60	0.35	0.12	1.25
	14	0.47	0.37	0.06	1.47
2	4	0.60	0.33	0.06	1.09
	7	0.86	0.47	0.12	1.96
	9	0.50	0.31	0.14	1.13
	14	0.51	0.40	0.01	1.26

The interaction was not statistically significant between group and implant (p=0.051).

The difference between implants was not statistically significant (p=0.395).

The difference between group 1 and group 2 was not statistically significant (p=0.151).

Table 9. Descriptive Analysis for Apical-Coronal Offset at Tip (in mm; n=15 per group)

Group	Implant	Mean	SD	Minimum	Maximum
1	4	0.28	0.12	0.06	0.48
	7	0.35	0.18	0.05	0.63
	9	0.33	0.21	0.02	0.80
	14	0.33	0.20	0.07	0.82
2	4	0.31	0.15	0.00	0.53
	7	0.28	0.14	0.06	0.50
	9	0.22	0.18	0.01	0.60
	14	0.19	0.13	0.04	0.37

The interaction was statistically significant between group and implant (p=0.040).

For implant #14, the difference between group 1 and group 2 was statistically significant (p=0.022).

Within group 1, the difference between implants was not statistically significant ($p=0.512$). Within group 2, the difference between implants was statistically significant ($p=0.021$). In post-hoc tests, the difference between implant #4 and implant #14 was significant ($p=0.007$).

Appendix B: Figures

Workflow from virtual planning to physical guided surgery:
Acquirement of CBCT scan (DICOM file) and model scan (STL file) ↓ Superimposition of DICOM file and STL file ↓ Virtual implant planning ↓ Virtual designing of surgical guide ↓ Fabrication of surgical guide ↓ Implant placement using surgical guide

Figure 1. Workflow from virtual planning to physical guided surgery.

Figure 2. A partial edentulous typodont with missing tooth #4 7 9 14 (#5 & 13 were not included)

Acquirement of model scan (STL file)
↓
Virtual implant planning
↓
Virtual designing of surgical guide
↓
Fabrication of surgical guide
↓
Implant placement using surgical guide
↓
Acquirement of post-op model scan (STL file)
↓
Superimposition of pre-op and post-op STL files
↓
Acquirement of data

Figure 3. Study workflow

Group 1 – **FASG***		
		
Group 2 – **SSG****		
Subgroup 2a	Subgroup 2b	Subgroup 2c
		

Figure 4. Study Groups

***FASG**: full arch surgical guide, extension from tooth #2 to tooth #15 with inspection windows on tooth #3 6 8 11

****SSG**: shortened surgical guide, supported by four abutment teeth

Subgroup 2a: Guide extension #2 3 X 6 X 8 with inspection windows on tooth # 3 6 8

Subgroup 2b: Guide extension #8 X 10 11 12 with inspection windows on tooth #8 11

Subgroup 2c: Guide extension #10 11 12 X 15 with inspection windows on tooth #11

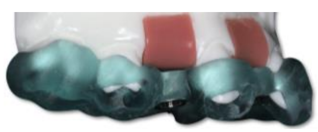
Group 1		
		
Group 2a	Group 2b	Group 2c
		

Figure 5. Inspections windows to check the seating of surgical guides

Figure 6. After implants were placed, scanbodies were placed with 15 N.cm

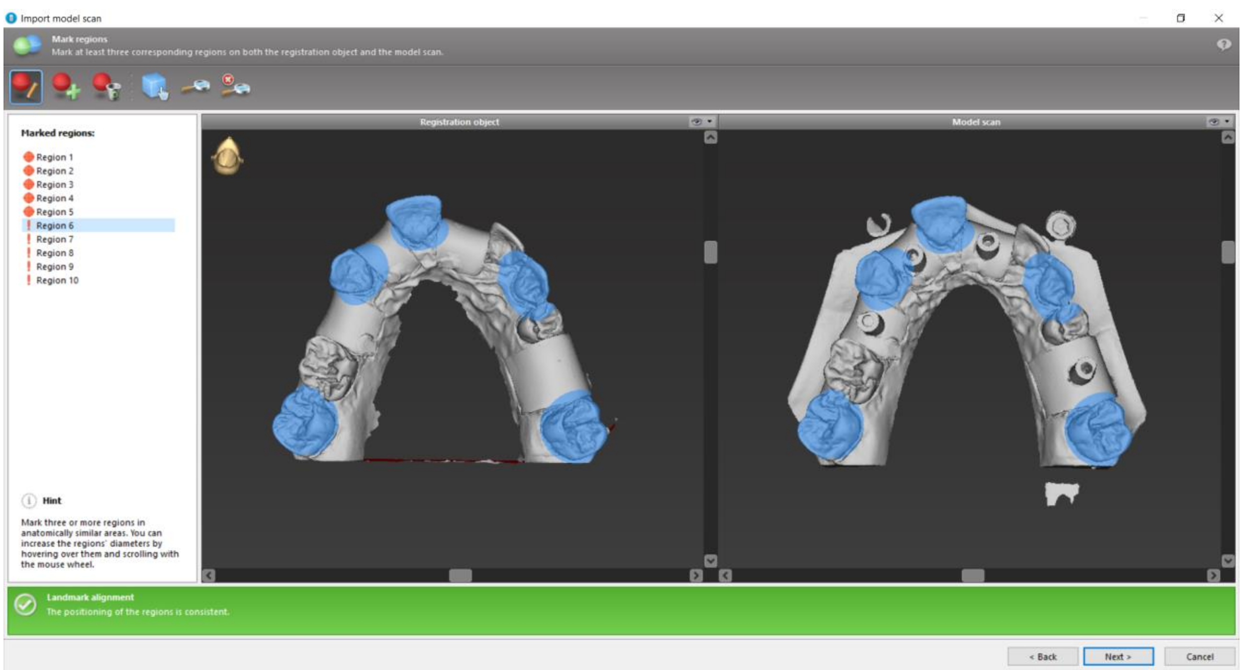


Figure 7. Superimposition of pre-op and post-op cast using tooth #2 #6 #8 #11 #15

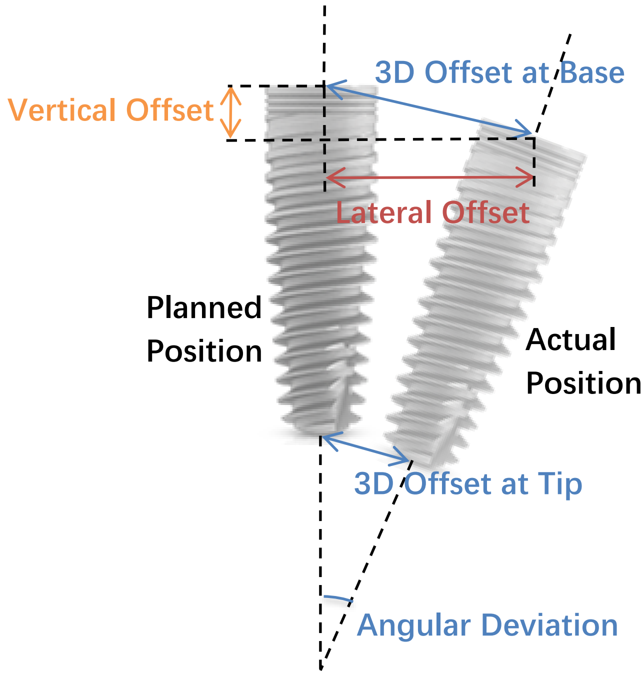


Figure 8. Diagram demonstrating deviation measurement

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