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Effect of metal sleeve integration on implant placement accuracy using additively manufactured tooth-supported surgical guides: an in vitro study

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Abstract

Background

This in vitro study evaluated whether the incorporation of metal sleeves influences implant placement accuracy when using additively manufactured tooth-supported surgical guides.

Methods

Thirty-two partially edentulous maxillary resin models were allocated to two groups: tooth-supported surgical guides with metal sleeves and sleeveless guides (n = 16 per group). Both guide designs were generated from the same virtual implant plan and manufactured using LCD-based vat photopolymerization. A VEGA implant measuring 4.0 × 10 mm was placed at the maxillary right second premolar site (FDI 15) in each model under standardized laboratory conditions. After implant placement, scan abutments were connected and the models were digitized using a laboratory scanner. The postoperative STL files were aligned with a master reference STL obtained from a physical reference model reproducing the planned implant position. Crestal horizontal, crestal vertical, and angular deviations were measured. Between-group differences were assessed using the Mann–Whitney U test, with the significance level set at $\alpha = 0.05$.

Results

No statistically significant differences were identified between the sleeveless and metal-sleeved groups for crestal horizontal deviation (median: 0.36 vs. 0.28 mm; $p = 0.287$), crestal vertical deviation (median: 0.53 vs. 0.63 mm; $p = 0.402$), or angular deviation (median: 8.00° vs. 10.00°; $p = 0.171$).

Conclusions

Under the conditions of this in vitro study, the incorporation of metal sleeves did not significantly influence the accuracy of implant placement using additively manufactured tooth-supported surgical guides. Sleeveless guides achieved accuracy comparable to that of metal-sleeved guides and may represent a viable alternative when appropriate digital planning, manufacturing, and guided surgical protocols are followed. Further clinical studies are required to confirm these findings.

Background

Static computer-assisted implant surgery (s-CAIS) is used to transfer a virtually planned implant position to the surgical field through a patient-specific guide. The final accuracy of implant placement reflects the cumulative performance of image acquisition, surface scanning, data registration, virtual planning, guide design and manufacture, guide seating, osteotomy preparation, implant insertion, and postoperative

position assessment [1–3]. Tooth-supported guides generally provide favorable stability in partially edentulous situations, but deviations between planned and achieved implant positions remain unavoidable.

Vat-photopolymerization additive manufacturing enables rapid fabrication of patient-specific surgical guides using biocompatible photopolymer resins. Nevertheless, the dimensional and functional performance of a guide can be influenced by printer technology, build parameters, support placement, post-processing, sterilization or disinfection, storage, and the geometry of the drill-guidance region [4, 5]. The interface between the drill and the guide is particularly relevant because small manufacturing tolerances or rotational play may be amplified along the length of the osteotomy.

Conventional guided systems commonly incorporate prefabricated metal sleeves to provide a rigid, wear-resistant drilling interface. However, sleeves increase component cost, require a specific housing geometry, may reduce irrigation access, and can limit guide design when the available interocclusal space is restricted. Sleeveless guides instead direct the drills through a printed polymer channel, simplifying the digital workflow and reducing the number of components. Evidence comparing both designs is mixed. Some in vitro studies have reported comparable accuracy between sleeved and sleeveless guides [6], whereas others found greater accuracy with sleeveless designs [7, 8]. Sleeve height, guide-to-implant distance, drill–sleeve clearance, guide-hole design, and the specific guided surgery system may explain part of this variability [9, 10]. A recent systematic review and meta-analysis found no significant overall differences in angular or horizontal deviation, but emphasized the limited number and predominantly in vitro nature of the available studies [11].

Accordingly, this in vitro study evaluated the influence of metal sleeve integration on implant placement accuracy using additively manufactured tooth-supported surgical guides. The null hypothesis was that no significant differences would be observed between sleeved and sleeveless guides in crestal horizontal, crestal vertical, or angular deviation from the planned implant position.

Methods

Study design

This experimental in vitro study evaluated the effect of metal sleeve integration on the accuracy of implant placement using additively manufactured tooth-supported surgical guides. Thirty-two resin models derived from the same digital design and representing a posterior partially edentulous maxilla with a missing maxillary right second premolar (FDI 15) were included. Each model received one implant and constituted one experimental unit.

The models were allocated in a 1:1 ratio to two experimental groups: tooth-supported surgical guides without metal sleeves (sleeveless group; SA; n = 16) and tooth-supported surgical guides with metal sleeves (metal-sleeved group; CA; n = 16). The presence or absence of the metal sleeve was the

experimental factor. The planned implant position, tooth support, guide thickness, manufacturing workflow, drilling sequence, and implant placement protocol were standardized between groups.

Sample size calculation and group allocation

An a priori sample size calculation was performed using GRANMO version 7.12 (Institut Municipal d'Investigació Mèdica, Barcelona, Spain) for the comparison of a continuous linear implant placement deviation between two independent groups. Assuming a two-sided α level of 0.05, a statistical power of 80%, a 1:1 allocation ratio, a common standard deviation of 0.5 mm, and a minimum detectable between-group difference of 0.5 mm, corresponding to a standardized effect size of 1.0, the required sample size was 16 experimental units per group, resulting in a total of 32 models.

The 32 experimental models were consecutively numbered and randomly allocated in a 1:1 ratio to the SA and CA groups using a computer-generated random sequence in Microsoft Excel (Microsoft Corp., Redmond, WA, USA). The order of implant placement and subsequent measurements was randomized.

Reference dataset and virtual implant planning

The digital workflow was based on a previously acquired and fully anonymized cone-beam computed tomography (CBCT) dataset in Digital Imaging and Communications in Medicine (DICOM) format and a corresponding Standard Tessellation Language (STL) file obtained by intraoral scanning. Both datasets originated from a posterior partially edentulous maxillary clinical case with a missing maxillary right second premolar (FDI 15), retrieved from the database of the University Dental Clinic of Universidad Europea de Madrid. The datasets were used exclusively to reproduce the anatomical geometry required for virtual implant planning and fabrication of the experimental models. No identifiable patient information, clinical variables, or treatment outcomes were accessed or analyzed.

The DICOM and STL datasets were imported into exoplan software with the Guide Creator module (exocad GmbH, Darmstadt, Germany). The datasets were superimposed to generate a combined three-dimensional representation of the anatomical and dental structures. Registration accuracy was visually verified by assessing the correspondence between the dental surfaces in multiple three-dimensional views.

A VEGA implant measuring 4.0 mm in diameter and 10 mm in length (Klockner Implant System, Barcelona, Spain) was virtually positioned at the maxillary right second premolar site (FDI 15). Implant planning was prosthetically driven and considered the available anatomical volume, adjacent anatomical structures, and the intended restorative axis. The final planned implant position was maintained unchanged for all experimental models.

Surgical guide design

Two tooth-supported surgical guide designs were generated from the same virtual implant plan, and a separate STL file was obtained for each design. In the sleeveless group (SA), the osteotomy drills were guided directly through the cylindrical channel formed in the printed resin structure. In the metal-sleeved group (CA), a prefabricated metal sleeve (reference 20 03 14 C-A, Klockner Implant System, Barcelona, Spain) was incorporated into the surgical guide to control the drilling path.

The planned implant position, tooth-supported extension, guide thickness, drilling diameter, and surgical protocol were maintained consistently between the two designs. Therefore, the presence or absence of the metal sleeve was the only experimental design factor.

For the CA group, the metal sleeves were inserted into the corresponding printed housing before the final post-curing procedure. Proper seating and adaptation of each sleeve within the resin guide structure were verified before the experimental procedures (Fig. 1).

Additive manufacturing and post-processing

Manufacturing of the experimental models

The experimental models were manufactured from the corresponding STL files using a Form 3 + vat-photopolymerization printer (Formlabs Inc., Somerville, MA, USA), Model Resin V3, and PreForm software version 3.54. After printing, the models were washed in isopropyl alcohol using a Form Wash unit and subsequently post-cured using a Form Cure unit (Formlabs Inc.). Washing and post-curing were performed in accordance with the resin manufacturer's recommendations to ensure adequate polymerization and dimensional stability of the printed models.

Manufacturing of the surgical guides

The surgical guides were manufactured from the corresponding STL files using an AccuFab-L4D LCD-based vat-photopolymerization printer (SHINING 3D, Hangzhou, China), SG01 Surgical Guide resin, and AccuWare software version 3.2.1.109.

After printing, the guides were washed in isopropyl alcohol using a FabWash unit and subsequently post-cured using a FabCure unit. Washing and post-curing were performed in accordance with the resin manufacturer's recommendations to minimize dimensional alterations and ensure adequate mechanical properties of the printed guides.

For the metal-sleeved group (CA), the prefabricated metal sleeves (reference 20 03 14 C-A, Klockner Implant System, Barcelona, Spain) were inserted into the corresponding printed housings after washing and before final post-curing. Proper seating and adaptation of each sleeve within the resin structure were verified before the experimental procedures. All surgical guides were sterilized before implant placement.

Guided implant placement

Implant placement was performed on the printed models using a fully guided surgical protocol. All procedures were carried out by a single operator to minimize operator-related variability.

Osteotomies were prepared using the Sniper guided surgery kit (Klockner Implant System, Barcelona, Spain) for VEGA implants measuring 4.0 mm in diameter and 10 mm in length. The drilling sequence was performed according to the manufacturer's recommendations, beginning with the lance drill, followed by the pilot drill and the progressively larger-diameter drills included in the corresponding surgical protocol. Drilling was performed at 1100 rpm under continuous irrigation. After completion of the osteotomy preparation, the implants were placed according to the previously established virtual implant plan (Fig. 2).

Post-placement digitization and three-dimensional analysis

After implant placement, a VEGA i-RV 1 Scan Abutment (Klockner Implant System, Barcelona, Spain) was connected to each implant. The flat antirotational surface of the scan abutment was oriented buccally in all models to standardize its rotational position and minimize potential digital alignment errors.

Before digitization, an opacifying scanning spray (Occlusion Spray, Proclinic) was applied to reduce surface reflections and facilitate digital acquisition. Each experimental model was digitized using a D2000 extraoral laboratory scanner (3Shape, Copenhagen, Denmark) at Prótesis S.A. dental laboratory (Madrid, Spain), generating an individual postoperative STL file for each model.

The postoperative STL files were imported into exocad software. The corresponding virtual scan-abutment geometry was automatically recognized by the software and used to digitally reconstruct the three-dimensional position and longitudinal axis of each implant. The STL files containing the digital scan abutments and their respective implant axes were subsequently exported and imported into Geomagic Wrap 2024 (3D Systems, Rock Hill, SC, USA).

To obtain the master reference STL, an additional reference model was printed and prepared to receive an implant replica at the virtually planned position. A scan abutment was connected to the implant replica, and the reference model was digitized using the same scanning workflow as the experimental models. The resulting STL file, containing the digital scan abutment and its reconstructed implant axis, was used as the master reference for the subsequent comparisons.

Each experimental STL file was aligned with the master STL in Geomagic Wrap 2024. An initial manual registration was followed by a global best-fit registration to obtain the final three-dimensional superimposition. After alignment, the discrepancies between the planned and placed implant positions were measured.

The following outcomes were evaluated:

1. Horizontal crestal deviation (HCD) (mm): horizontal linear discrepancy between the planned and placed implant positions at the crestal level.
2. Vertical crestal deviation (VCD) (mm): vertical linear discrepancy between the planned and placed implant positions at the crestal level.
3. Angular deviation (AD) (°): three-dimensional angle between the longitudinal axes of the planned and placed implants.

Horizontal, vertical, and angular deviations were recorded as non-negative magnitudes representing the discrepancy between the planned and final implant positions (Fig. 3).

Statistical analysis

The model was considered the experimental unit, with one implant and one set of measurements obtained from each model. Statistical analyses were performed using IBM SPSS Statistics version 31.0 (IBM Corp., Armonk, NY, USA). Continuous variables were summarized using the mean, standard deviation, median, interquartile range, minimum, and maximum. Normality was assessed separately for each outcome and group using the Shapiro–Wilk test. Because several variables did not follow a normal distribution, crestal horizontal, crestal vertical, and angular deviations were compared between the sleeveless and metal-sleeved groups using the Mann–Whitney U test for independent samples. All tests were two-sided, and the significance level was set at $\alpha = 0.05$.

Results

All 32 experimental models were successfully completed and included in the final analysis, with 16 models in each group. Descriptive statistics for crestal horizontal, crestal vertical, and angular deviations are presented in Table 1.

Outcome	SA, n = 16 Median (IQR)	CA, n = 16 Median (IQR)	SA range	CA range	Mann–Whitney U	p value
HCD (mm)	0.36 (0.23–0.71)	0.28 (0.16–0.39)	0.06–1.60	0.08–1.80	99.0	0.287
VCD (mm)	0.53 (0.36–0.79)	0.63 (0.48–0.80)	0.23–1.35	0.26–3.09	105.0	0.402
AD (°)	8.00 (6.00–11.00)	10.00 (8.00–11.50)	0–12	4–15	91.5	0.171

Table 1 Descriptive statistics and intergroup comparisons of implant placement deviations. Data are presented as median (IQR) and range. SA, sleeveless group; CA, metal-sleeved group; HCD, horizontal crestal deviation; VCD, vertical crestal deviation; AD, angular deviation; IQR, interquartile range. Between-group comparisons were performed using the Mann–Whitney U test.

Both surgical guide designs showed measurable deviations between the planned and final implant positions. However, no statistically significant differences were identified between the sleeveless and metal-sleeved groups for crestal horizontal deviation ($U = 99.0$, $p = 0.287$), crestal vertical deviation ($U = 105.0$, $p = 0.402$), or angular deviation ($U = 91.5$, $p = 0.171$) (Fig. 4). The null hypothesis was therefore not rejected for any of the evaluated outcomes.

Discussion

The principal finding of this in vitro study was that integrating a metal sleeve into an additively manufactured tooth-supported surgical guide did not significantly improve implant placement accuracy. Crestal horizontal, crestal vertical, and angular deviations were comparable between the sleeved and sleeveless groups. Both designs nevertheless showed measurable discrepancies from the virtual plan, demonstrating that neither guide configuration eliminated the cumulative error inherent to the digital and surgical workflow.

The absence of significant intergroup differences is consistent with the findings of Adams et al., who reported broadly comparable implant-position deviations for guides with and without metal sleeves [6]. It is also consistent with the recent systematic review and meta-analysis by Esperouz et al., which found no significant pooled differences in angular or horizontal deviation between guide designs, although only four studies were eligible and most evidence was derived from laboratory models [11]. These similarities support the view that a metal sleeve is not, by itself, a guarantee of greater transfer accuracy.

Other investigations have reported greater accuracy for sleeveless designs. Hang and Guentsch observed lower angular and linear deviations with sleeveless guides and found that accuracy decreased as the distance from the guidance region to the implant platform increased [7]. Raabe et al. also reported smaller mean angular, crestal, and apical deviations with a sleeveless guide-hole design than with a manufacturer's sleeve in a keyless guided system [8]. Conversely, studies comparing different sleeve geometries have shown that closed metal sleeves may outperform some open polymer guide-hole designs [9]. These apparently divergent results likely reflect differences in implant systems, drill stabilization, guide-hole geometry, sleeve height, drilling distance, drill–sleeve clearance, model morphology, guide support, and measurement methods rather than the presence of metal alone [9, 10].

The deviations detected in both groups should be interpreted as the accumulated result of multiple steps. Registration of CBCT and surface-scan datasets, manufacturing and post-processing of the resin models and guides, seating of the guide, drill wear, operator handling, implant insertion, scan-abutment connection, laboratory scanning, library matching, and STL registration may each contribute to the final discrepancy [1–5, 12–15]. Consequently, a lack of difference between guide designs does not imply perfect reproduction of the virtual plan. It indicates only that, under the tested conditions, the addition of a metal sleeve did not measurably reduce the selected deviations.

Sleeveless guides may offer practical advantages by reducing the number of components, simplifying manufacturing, avoiding a separate sleeve-insertion step, and facilitating use where interocclusal space

is limited. However, these potential benefits must be balanced against possible polymer wear, deformation, heat generation, surface damage, and sensitivity to the dimensional accuracy of the printed channel. The current experiment assessed final implant position but did not directly quantify guide-hole wear, surface roughness, thermal effects, or changes after repeated drilling. Therefore, the results should not be interpreted as evidence that sleeveless guides are interchangeable with metal-sleeved guides in every implant system or clinical situation.

This study has several limitations. First, the in vitro model did not reproduce saliva, limited mouth opening, soft-tissue displacement, patient movement, bone-density variability, or clinically relevant guide-stabilization challenges. Second, only one posterior maxillary edentulous site (FDI 15), one implant system and dimension, one guide-support configuration, one printer–resin combination for the surgical guides, and one post-processing protocol were evaluated. Third, all implant placements were performed by a single operator; this reduced interoperator variability but limits generalizability. Fourth, the findings depend on the accuracy of the reference dataset and the postoperative digital measurement workflow. Fifth, the study did not evaluate apical deviation, quantitative guide fit, drill-channel wear, mechanical properties, repeated use, or the effects of sterilization and storage. Finally, no repeated-measurement reliability analysis was performed, and several manufacturing and guide-interface parameters were unavailable, limiting assessment of their individual contribution to the observed deviations.

Further studies should compare sleeved and sleeveless guides across different implant systems, guide-to-implant distances, channel geometries, polymer materials, and clinical scenarios. Mechanical and dimensional assessment of the guide-hole region before and after drilling would help clarify whether equivalent implant-position accuracy is maintained when polymer wear, repeated use, or lateral loading is introduced. Clinical studies are also required before broad recommendations can be made.

Conclusions

Within the limitations of this in vitro study, both metal-sleeved and sleeveless additively manufactured tooth-supported surgical guides showed deviations from virtual planning, with no statistically significant differences in crestal horizontal, crestal vertical, or angular implant placement accuracy. Sleeveless guides may therefore represent a viable alternative in selected situations when appropriate planning, manufacturing, and surgical protocols are followed.

Abbreviations

CA
metal-sleeved group
CBCT
cone-beam computed tomography
DICOM
Digital Imaging and Communications in Medicine

IQR
interquartile range
LCD
liquid crystal display
SA
sleeveless group
s-CAIS
static computer-assisted implant surgery
STL
Standard Tessellation Language.

Declarations

Ethics approval and consent to participate

Not applicable. This experimental in vitro study was conducted exclusively on additively manufactured resin models. The DICOM and STL datasets used to reproduce the anatomical geometry of the experimental model had been previously acquired for clinical purposes and were fully and irreversibly anonymized before being accessed for the present research. No identifiable or re-identifiable patient information, clinical variables, biological specimens, additional radiographic examinations, clinical interventions, or treatment outcomes were collected or analyzed. In accordance with Recital 26 of Regulation (EU) 2016/679 and the definition of anonymized or irreversibly dissociated data provided by Spanish Law 14/2007 on Biomedical Research, the datasets used in this study did not constitute identifiable human data. Therefore, formal ethics approval and informed consent to participate were considered not applicable. All procedures were conducted in accordance with applicable institutional, national, and international guidelines and regulations.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests. Klockner Implant System provided materials for the experimental procedures but had no role in study design, data collection, analysis, interpretation, manuscript preparation, or the decision to submit the article for publication.

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Authors' contributions

D.R.M, I.G.G., P.S.H and F.L.M.; Methodology: D.R.M. and F.L.M.; Software: D.R.M., P.S.H and F.L.M.; Validation: P.R.V and J.J.G; Formal analysis: D.R.M. and E.C.G; Investigation: S.Z.R. and E.C.G; Resources: P.R.V and J.J.G; Data curation: D.R.M. and J.P.; Writing—original draft preparation: I.G.G; Writing— review and editing: E.C.G, P.R.V, P.S.H, J.J.G; Visualization: I.G.G.; Supervision: P.R.V and J.J.G; Project administration: P.R.V and J.J.G. All authors have read and approved the published version of the manuscript.

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Figures

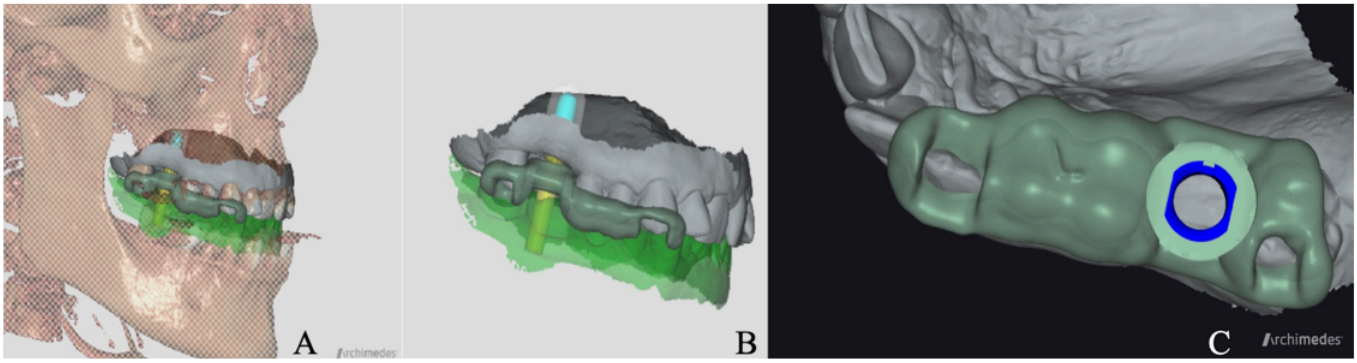


Figure 1

Registration of the CBCT and surface-scan datasets, virtual implant planning, and design of the tooth-supported surgical guide with a metal sleeve using exoplan software.

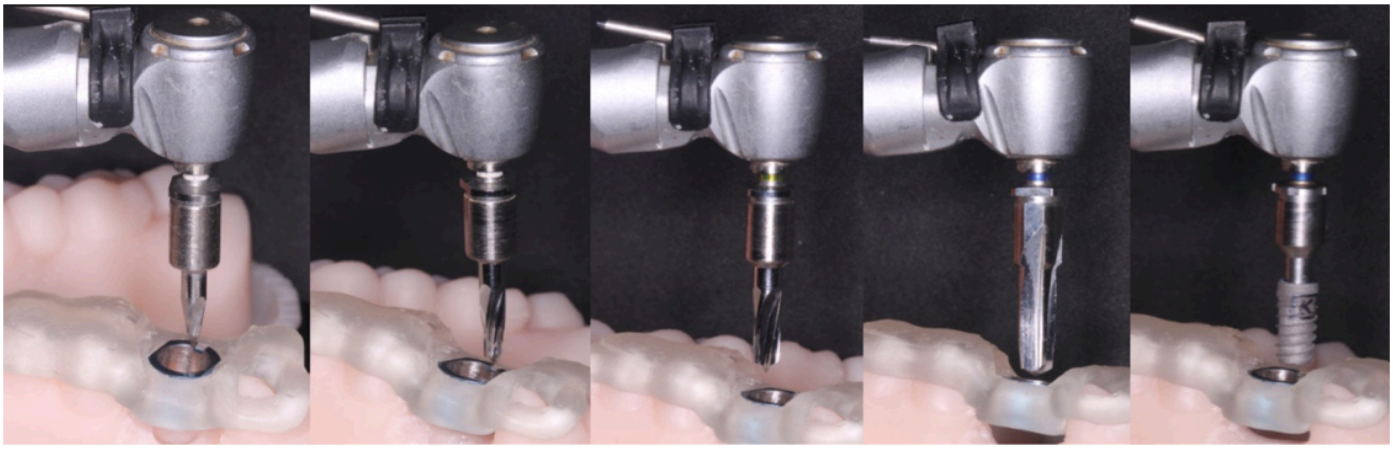


Figure 2

Standardized guided drilling and insertion protocol for placement of a VEGA 4.0 × 10 mm implant.

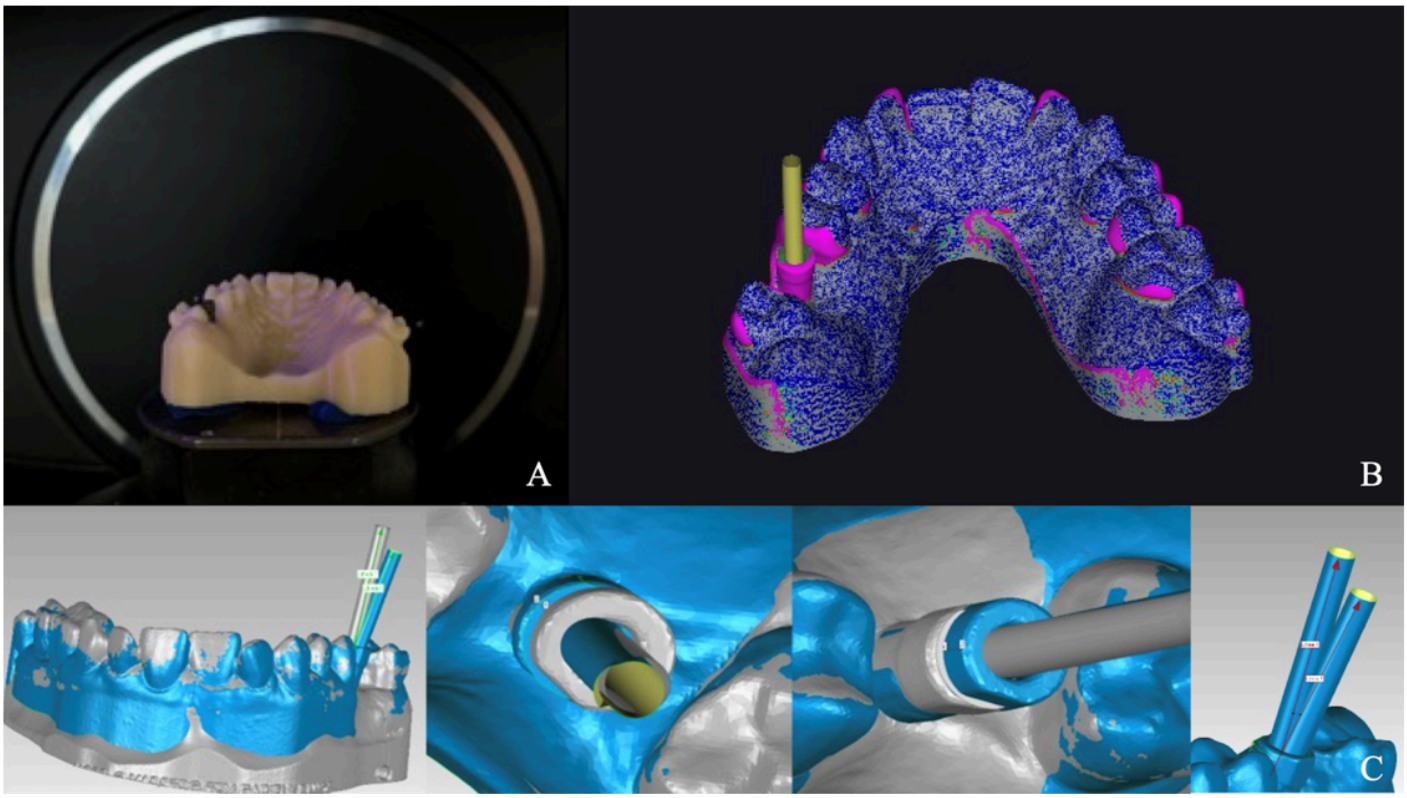


Figure 3

Post-placement digital workflow. (a) Laboratory scanning of the model with the scan abutment connected. (b) Generation of the post-placement STL file. (c) Registration of the experimental and reference STL files, reconstruction of implant axes, and measurement of crestal horizontal, crestal vertical, and angular deviations in Geomagic Wrap 2024.

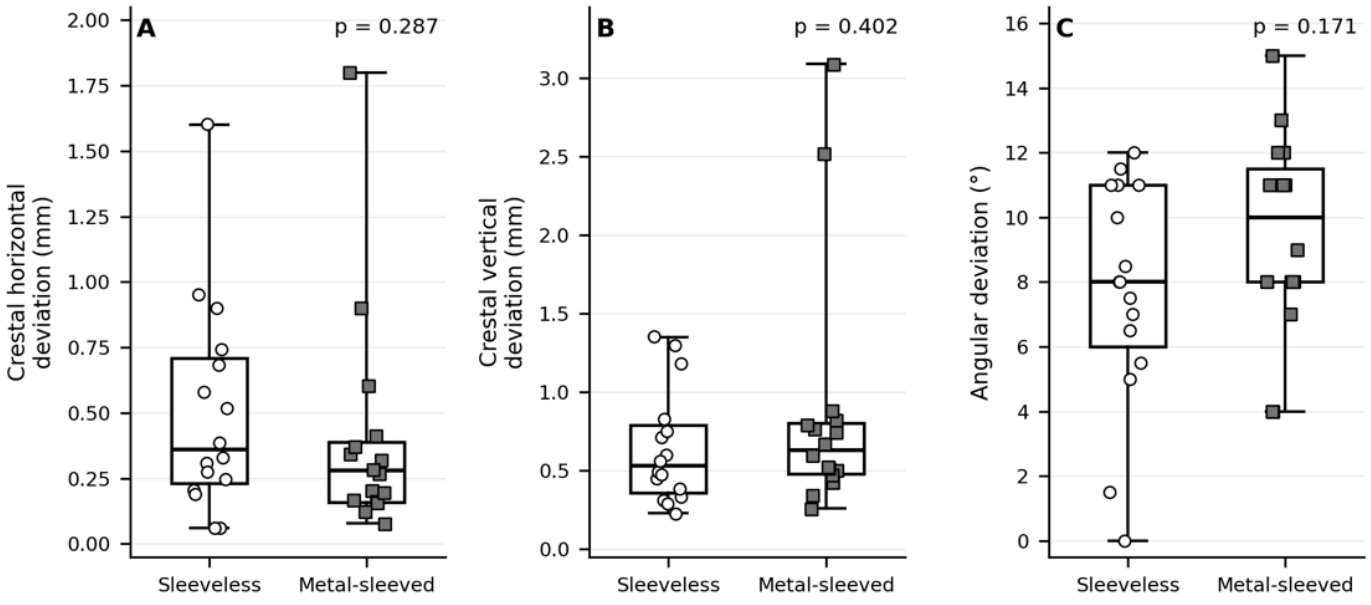


Figure 4

Comparison of implant placement deviations between sleeveless and metal-sleeved surgical guides. Boxplots show the median, interquartile range, and individual observations for (a) crestal horizontal deviation, (b) crestal vertical deviation, and (c) angular deviation. Between-group comparisons were performed using the Mann–Whitney U test (n = 16 per group).

Supplementary Files

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- TableSupplementary1.docx
- TableSuplementary2.docx