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RESEARCH AND EDUCATION

Influence of 3D- printing method, resin material, and sterilization on the accuracy of virtually designed surgical implant guides

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ABSTRACT

Statement of problem. Three-dimensional printing has introduced new manufacturing methods. However, information on the influence of the specific printing technology, material, sterilization, and the comparison between printing and milling on the accuracy of surgical guides is lacking.

Purpose. The purpose of this in vitro study was to evaluate the influence of the manufacturing method (printing and milling), printing technology stereolithography (SLA) and digital light processing (DLP), material, and sterilization on the accuracy of digitally designed surgical implant guides.

Material and methods. Resin patient replicas with a single edentulous space were used to place 132 implants with digitally designed surgical guides. The accuracy of postoperative implant position was analyzed for the manufacturing method (printing and milling), resin materials, and preoperative autoclaving. To determine 3D accuracy, angular displacement, mean horizontal crestal, apical displacement, and the linear vertical displacement at the apex were calculated separately for each group (n=12). In addition, the surgical guides were qualitatively analyzed by using field emission scanning electron micrograph.

Results. The postoperative angular deviation ranged from 0.76 ±0.52 degrees (Rapidshape D20II with NextDent SG) to 2.43 ±0.64 degrees (Form2 with NextDent SG) (P<.001). Linear horizontal displacement at the crest was smallest for Rapidshape D20II with 3Delta Guide (0.27 ±0.08 mm) and highest for Form2 with NextDent SG (0.54 ±0.10 mm) (P<.001). Linear horizontal displacement at the apex ranged from 0.36 ±0.10 mm (SolFlex 350 with V-Print SG) to 0.89 ±0.32 mm (Form2 with NextDent SG) (P<.001). Considering the vertical position displacement was no more than 0.43 ±0.07 mm (Form2 with NextDent SG) short of the apex, none of the implant tips were displaced apically. Preoperative autoclaving differentially impaired the accuracy of surgical guides.

Conclusions. The specific manufacturing technique, the 3D printing device, the resin material, and the application of preoperative sterilization all affected the accuracy of the postoperative implant position. Irrespective of the manufacturing method, all implants were placed within the commonly accepted safety distance. (J Prosthet Dent 2020;■:■-■)

Improper dental implant placement may lead to the breakdown of osseointegration, peri-implantitis, or unsatisfactory esthetic outcomes, resulting in unfavorable long-term outcomes.[1,2] During implant planning, special attention has to be paid to critical anatomic structures, including the mandibular canal, maxillary sinus, and adjacent teeth. Preoperative surgical implant planning is increasingly based on 3D radiographic methods, particularly cone beam computed tomography (CBCT) scanning.[3] The optimal implant position can be virtually designed by digitally matching the CBCT data and the data from a scan of the diagnostic cast and then transferring it into the clinical situation with a surgical guide.[4,5] Recently, surgical implant guides have been 3D-printed to overcome the disadvantages of subtractive milling.[6-8] The most commonly used and cost-effective method in dentistry has been stereolithography (SLA) and the related digital light processing (DLP) technique. SLA uses an ultraviolet (UV) laser or laser diode to draw a cross-section layer by layer to build the printed object.

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Clinical Implications

Three-dimensional printing of resin material is appropriate for the manufacturing of surgical guides and has similar accuracy to 5-axis milled surgical templates. Preoperative autoclaving of surgical guides can be recommended especially for the DLP-printed materials.

DLP uses a digital projector screen to transfer a single image of each layer across the entire build plate. Materials appropriate for printing surgical guides are typically based on methyl methacrylate. During surgical implant placement, these materials closely contact the surgical site. Therefore, these are Class I or Class II medical products and are approved for steam heat sterilization.[9-11]

Research in the field of guided implant surgery has mainly focused on the analysis of the accuracy and reliability of the implant position transfer from virtual planning to the surgical site.[12-16] Information on the influence of the specific production method on the accuracy of surgical guides is lacking.[17-19] Therefore, the purpose of this in vitro study was to delineate the quality of the implant position transfer with 5-axis milled and DLP and SLA 3D-printed surgical guides. The null hypotheses were that the subtractive or additive manufacturing of the templates, the 3D printing material, and the sterilization of the device would not affect the accuracy of the implant position.

MATERIAL AND METHODS

The study was conducted by using a clinical patient situation with a single edentulous space at the right maxillary second premolar region scheduled for implant placement. The study was approved by the local ethics committee (project number 20-653KB/2020). Preoperative CBCT (Kodak 9300, 5×5×5 cm, 78 kV, 6.3 mA, 20s; Kodak Corp) and an impression (Impregum; 3M) of the relevant area were available. The master model (CEREC Stone BC; Dentsply Sirona) was digitalized with a laboratory scanner (Activity 885 Mark 2; smart optics GmbH), and a total of 132 resin replicas (picopoly; picodent GmbH) were made by using a silicone mold (Adisil rosé; SILADENT GmbH). To control for conformity between the master model and the replicate models, a surface scan was made from each resin replica. The resulting standard tessellation language (STL) data sets were superimposed by using a software program (CloudCompare; www.cloudcompare.com).

For the digital planning of implant position, the STL file of the resin replica scan and digital imaging and communications in medicine (DICOM) data of CBCT were uploaded into a dedicated software program (coDiagnostix; Dental Wings Inc). Both data files were digitally matched by using easily defined anatomic landmarks, primarily the natural teeth and attached gingiva. Before virtual implant placement, the missing tooth was digitally waxed. The 3D implant position was planned for 1 specific type of dental implant with appropriate length and diameter (tissue level implant; 10 mm length, diameter: 4.1 mm; Institut Straumann AG). For the digital design, the surgical guide was fixed on both sides to 2 adjacent teeth. The distance of the sleeve to the crest was set on H4 (4.0 mm above the cast).[20] Material thickness was set to 2 mm and the guide was offset to the teeth by 0.05 mm. Subsequently, the surgical guides were manufactured by using either an additive or a subtractive method.

The STL file was imported for additive manufacturing individually adapted to the specific material and printing device into the corresponding nesting software program, and material-dependent printing parameters were selected (Fig. 1). The surgical guides were nested 30 degrees to the building platform and support structures were added. They were sliced as per the manufacturer's settings with corresponding layer thickness. G-codes were transmitted to the printers for the respective resin material (Tables 1 and 2).

For surgical guide fabrication with the subtractive method, the STL file was imported into the software program (InLab Cam 18.0; Dentsply Sirona) for production with a 5-axis milling device (MCX5, minimum bur head diameter: 0.5 mm; Dentsply Sirona). Postprocessing was carried out as per the manufacturer's specification and included ultrasonic cleaning of the printed templates for 3 minutes in 96% isopropanol, drying, and postpolymerization depending on the material (Fig. 1). Finally, the support structures were removed, and T-shaped metal drilling sleeves were inserted into the surgical guides (diameter: 5.0 mm; height: 5.0 mm; Institut Straumann AG). Surgical guides assigned to study groups designated for additional preoperative sterilization were steam autoclaved at 135 °C for 5 minutes (Selectomat PL3; MMM Group).

Sequential drilling and installation of the implants were performed as per a standardized protocol by 1 operator (M.D.) by using a fully guided surgery kit (Institut Straumann AG). All implants were finally inserted manually with the surgical guide by using the portable adaptor with a torque wrench. After completion of implant placement, scan bodies (Institut Straumann AG) were connected to the implant, and postoperative digital scans were made in the laboratory (Activity 885 Mark 2; smart optics GmbH). The generated STL files were imported into an implant planning software program (coDiagnostix; Dental Wings Inc) for superimposition on the preoperatively designed virtual implant

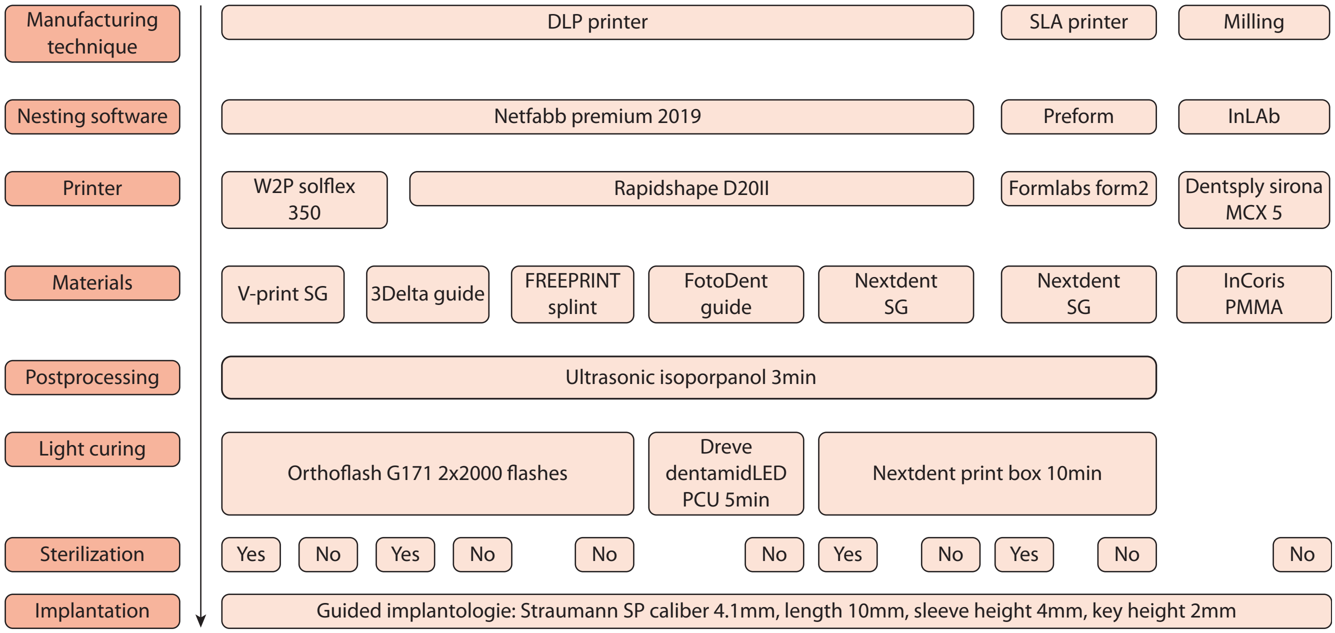

Figure 1. Study design.

Table 1. Brand names, manufacturers, wavelength λ, composition (as per manufacturer), and material classification of materials

Material	Manufacturer	λ [nm]	Matrix	Material Classification
3Delta Guide	DeltaMed GmbH	385	UDMA, TMPTA, TPO	I
FREEPRINT splint	DETAX GmbH	378-388	Acrylated resin, Aliphatic urethane acrylate, tripropyleneglycol diacrylate, THFMA, TPO	IIa
FotoDent guide	Dreve Dentamid	385	Ethoxyliertes(04) Bisphenol A Dimethacrylat, Acrylresin, 2-Hydroxyethylmethacrylat, Hydroxypropylmethacrylat, Monoester with 1,2-Propandiol, TPO	IIa
NextDent SG	NextDent	385	Methacrylic oligomers, Phosphine oxide	I
V-Print SG	VOCO GmbH	385	Bis-EMA, UDMA, TPO	IIa
InCoris PMMA guide	Dentsply Sirona	-	PMMA	I

Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; PMMA, polymethyl methacrylate; THFMA, tetrahydrofurfuryl methacrylate; TMPTA, trihydroxymethylpropyltriacrylate; TPO, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide; UDMA, Urethandimethacrylate.

position. Metric analysis between the virtual preoperative and real postoperative implant position was performed by using angular displacement of the long implant axis, horizontal 3D displacement of the implant crest and apex, and vertical displacement of the implant (Fig. 2).

For qualitative evaluation of the effect of preoperative sterilization, the surfaces of the surgical guides were analyzed with a reflected light microscope (BMS 74956; Breukhoven) at a magnification of ×4.5. In addition, representative specimens were analyzed with a field emission scanning electron micrograph (FE-SEM) (DSM 982; ZEISS AG).

The data were tested within groups for normal distribution by using the Kolmogorov-Smirnov test. Homogeneity of variances was analyzed with the Levene test. Differences between planned and postoperative implant positions were analyzed separately for each parameter by using the unpaired sample t test (α=.05). A statistical software program (IBM SPSS Statistics, v25.0; IBM Corp) was used for the analyses.

Table 2. Brand names, manufacturers, wavelength λ, technologies of printers and milling device

Printer and Milling Device	Manufacturer	λ [nm]	Technology
Rapidshape D20 II (RS)	Rapidshape GmbH	385	DLP
SolFlex 350 (SF)	W2P Engineering GmbH	385	DLP
Form2	Formlabs Inc	405	SLA
MCX5	Dentsply Sirona	-	5-axis milling

DLP, digital light processing; SLA, stereolithography.

RESULTS

Mean ±standard deviation angular displacement with surgical guides not receiving preoperative sterilization ranged from 0.83 ±0.56 degrees (Rapidshape D20II with

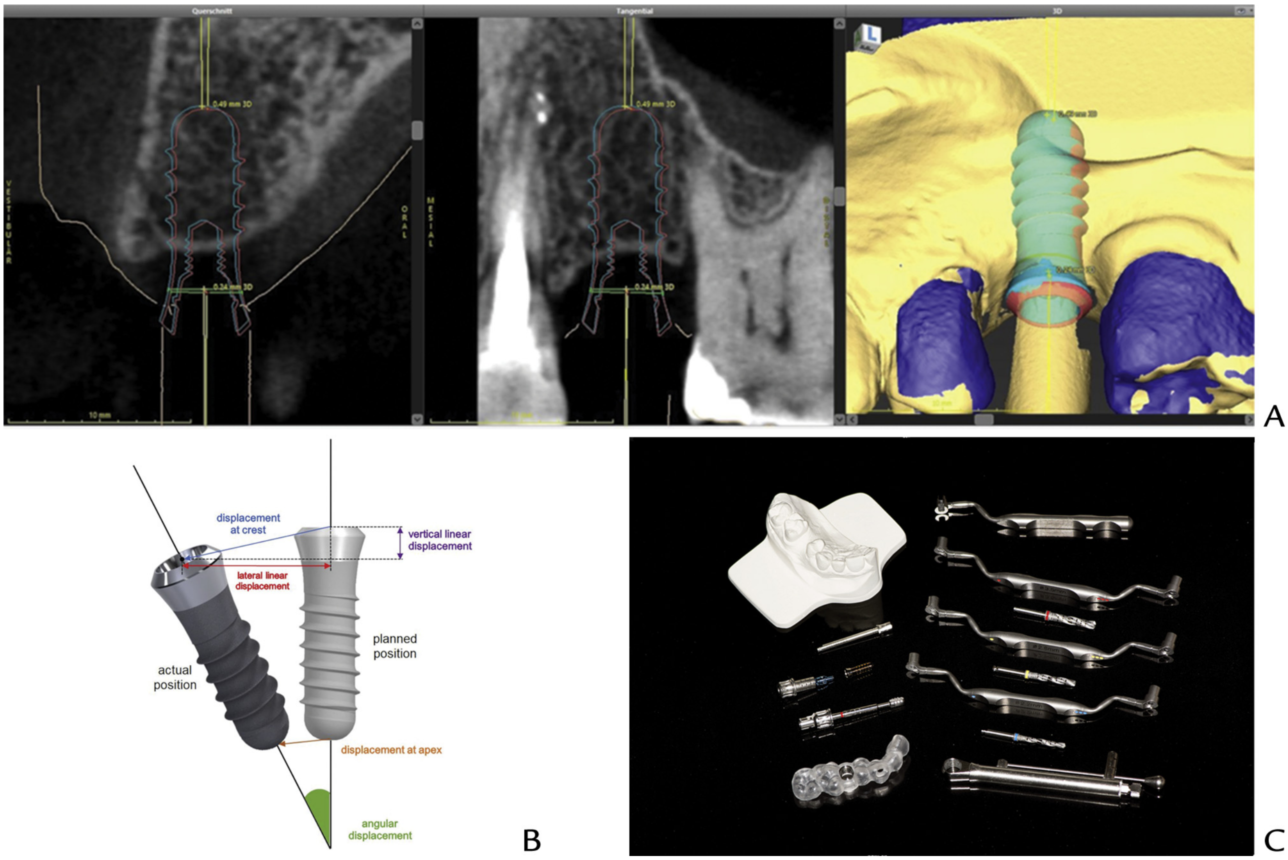

Figure 2. A, 3D evaluation of planned (*turquoise*) and placed implant (*red*). B, Schematic deviation measurements evaluated. C, Representative model, surgical guide, and instruments used.

FREEPRINT splint) to 2.18 ±1.20 degrees (Form2 with NextDent SG). The angular displacement between Rapidshape D20II with FREEPRINT splint and Form2 with NextDent SG was significantly different (*P*=.021). The angular deviation for the surgical guides that were sterilized was smallest for Rapidshape D20II with NextDent SG (0.76 ±0.52 degrees) and highest for Form2 with NextDent SG (2.43 ±0.64 degrees) (*P*<.001) (Figs. 3, 4).

The implant position at the crest and apex was dependent on both the printing device and the resin material. Surgical guides printed with Rapidshape D20II with 3Delta Guide had a mean ±standard deviation displacement of 0.27 ±0.08 mm at the crest and of 0.40 ±0.09 printed by Rapidshape D20II with FREEPRINT splint (*P*=.001). At the implant apex, the horizontal displacement ranged from 0.38 ±0.20 mm (Rapidshape D20II with NextDent SG) to 0.68 ±0.40 mm (Form2 with NextDent SG) (*P*=.032). Using preoperative sterilized surgical guides, the horizontal displacement at the crest amounted from 0.31 ±0.07 mm (SolFlex 350 with V-Print SG) to 0.54 ±0.10 mm (Form2 with NextDent SG) (*P*<.001). At the apex, the horizontal displacement was lowest for SolFlex 350 with V-Print SG (0.36 ±0.10 mm) and highest for Form2 with NextDent SG (0.89 ±0.32 mm) (*P*<.001).

The vertical postoperative implant position showed considerable crestal displacement irrespective of the printing device and resin material except for the 3Delta Guide device. Negative vertical values represent implant positions short of the designated apical length. Surgical guides not subjected to preoperative sterilization caused a vertical displacement of implants ranging from 0.09 ±0.07 mm (Rapidshape D20II with 3Delta Guide) to -0.38 ±0.08 mm (Rapidshape D20II with FREEPRINT splint) (*P*<.001), whereas the vertical displacement of implants inserted with surgical guides that had undergone sterilization was 0.00 ±0.16 mm (Rapidshape D20II with 3Delta Guide) to -0.43 ±0.07 mm (Form2 with NextDent SG) (*P*<.001).

Preoperative sterilization caused additional displacement of the implant at the crestal area (*P*=.017) and at the long axis (*P*<.001) for surgical guides that were manufactured with NextDent SG with Form2. In addition, surgical guides manufactured with NextDent SG and Rapidshape D20II had a significant difference in vertical displacement between sterilized and non-sterilized specimens (*P*=.002). Surgical guides made with V-Print had a higher angular (*P*=.013) displacement after sterilization. Implants placed with sterilized NextDent

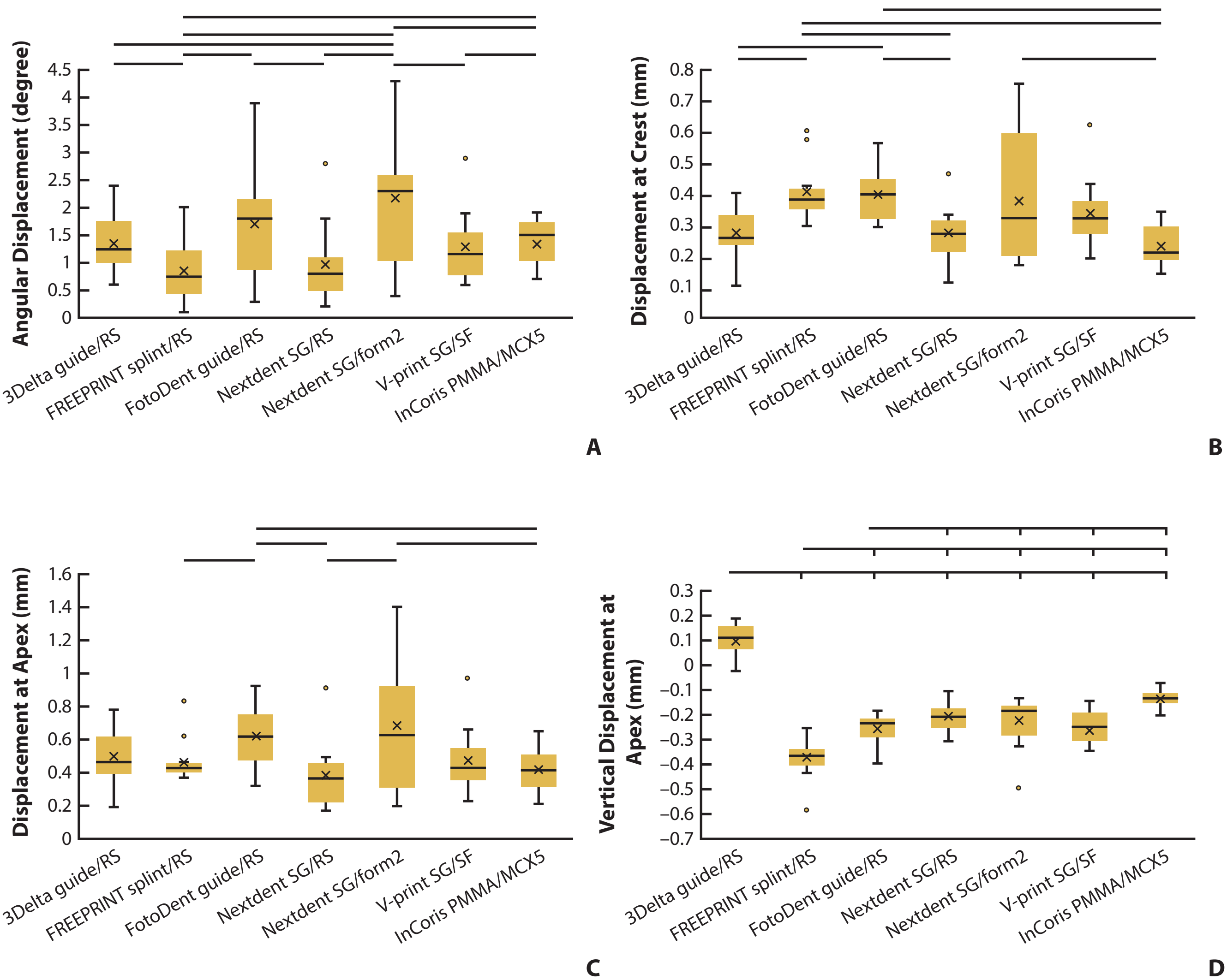

Figure 3. Measurements of deviation between planned and final implant position for different materials. A, Angular displacement (degree). B, Displacement at crest (mm). C, Displacement at apex (mm). D, Vertical displacement at apex (mm). Bars (mean ±standard deviation) connected by lines significantly different (*P*<.05).

SG guides had significantly higher angular (*P*<.001), crest (*P*<.001), apex (*P*<.001), and vertical (*P*=.001) displacement if the guides were printed with Form2 instead of Rapidshape D20II.

Figure 5 shows the surfaces of surgical guides manufactured with NextDent SG printed with Rapidshape D20II and Form2 before and after sterilization. SEM analysis revealed a characteristic surface ultrastructure. The surface of the guides printed with the Rapidshape D20II device showed sharply contoured Z-steps, which are printed homogeneously at a well-defined distance from each other. The surface of the guides printed with Form2 showed irregularly shaped horizontal Z-stepping with rounded edges of each layer. The surface is interrupted by vertical fissures leading to an irregular appearance of the Z-stepping. In addition, numerous deeper cracks appeared to have been induced by sterilization of the surgical guides processed with the resin NextDent SG and printed by the Form2 device.

DISCUSSION

Comparing the current in vitro results with those of previous in vivo studies, the precision of implant placement using different surgical guides was considerably higher.[12,15,16] This difference might be attributable to the specific study design comparing the virtual preoperative and postoperative implant position in resin replicas. Different from the experimental strategy as used in the present study, factors with considerable impact on the postoperative implant position, such as impaired

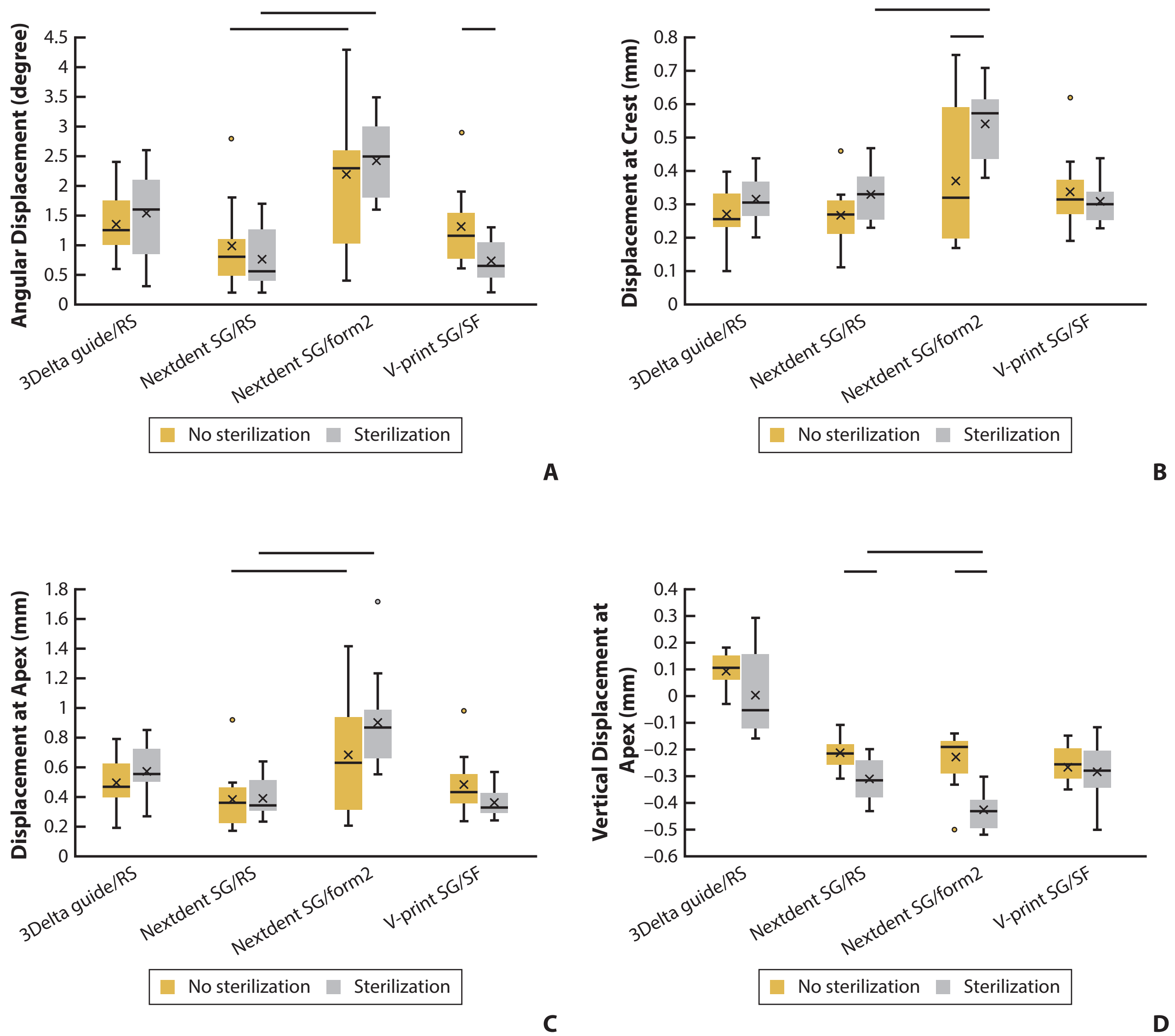

Figure 4. Measurements of deviation between planned and final implant position for different materials and sterilization. A, Angular displacement (degree). B, Displacement at crest (mm). C, Displacement at apex (mm). D, Vertical displacement at apex (mm). Bars (mean ±standard deviation) connected by lines significantly different ($P<.05$). Significance calculated within one material and between material Nextdent SG printed on DLP and SLA printer. DLP, digital light processing; SLA, stereolithography

intraoral visual control and patient movements, have to be taken into account in vivo. To be able to focus the analysis on the accuracy of the surgical guide itself and to control for confounding factors, high-resolution CBCT scanning was conducted with a small field of view. In addition, the STL surface scan of the experimental replicas was carried out with a high-precision laboratory scanner. To simulate actual clinical conditions as closely as possible, the implant length (10 mm), the sleeve distance (4 mm), and the drilling key height (1 mm) were set to a standard value in accordance with previous studies.[12,13,20] The comparison between preoperative and postoperative implant positions was performed with STL scans of a scan body mounted to the implant instead of digital matching of preoperative and postoperative CBCT scans to optimize precision.

No significant difference was found regarding the accuracy between most of the surgical guides that were manufactured by 3D printing or with a milling device, so the first part of the null hypothesis was partially accepted. However, subtractive manufacturing has some drawbacks as compared with 3D printing, for example, the wear of milling tools, limited access to undercuts, and increased processing time.[6,8,21] Studies comparing the accuracy of the implant placement of fully milled versus 3D-printed guided templates are sparse. One study using

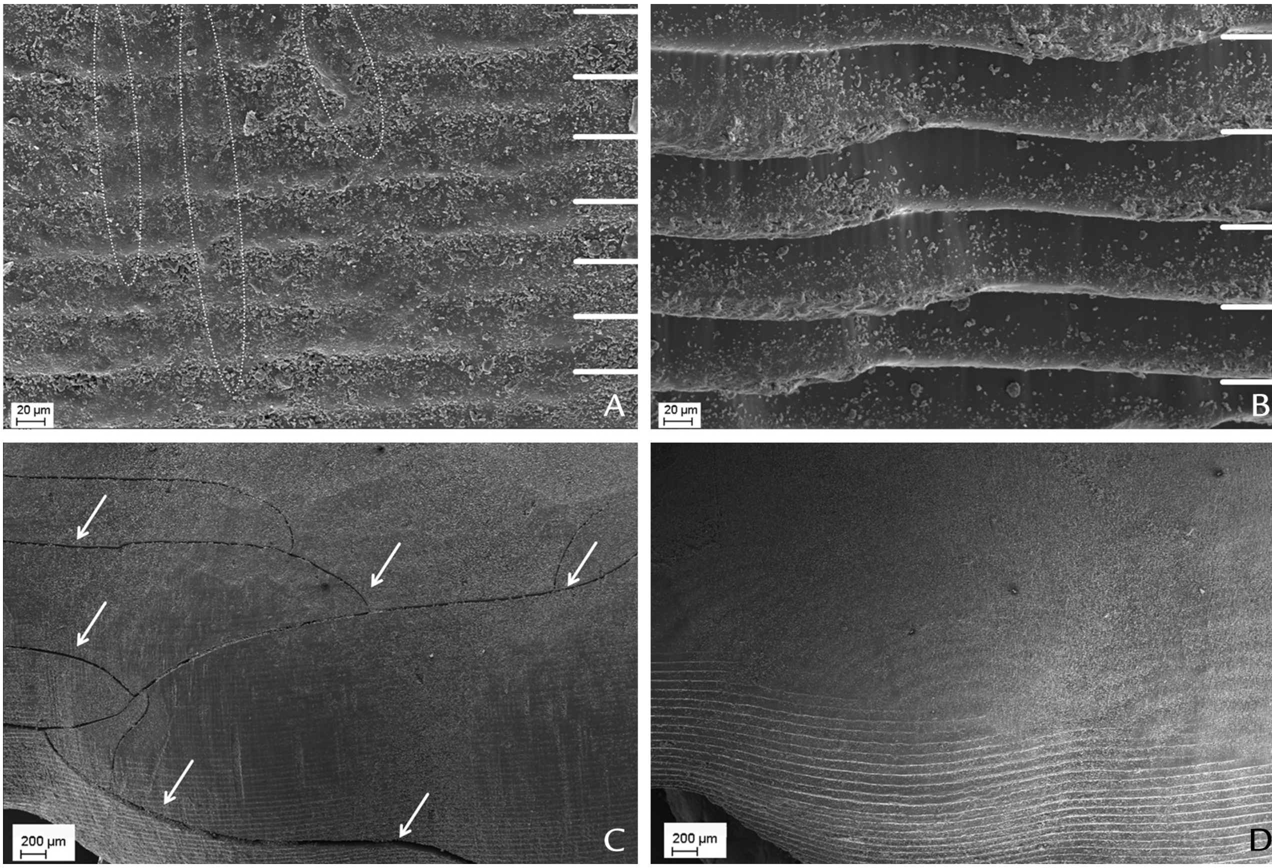

Figure 5. Representative scanning electron micrographs of surgical guide surfaces (Original magnification ×250 or ×20). Individual layers and Z stepping can be detected (*white lines*). Layers interrupted by vertical indentations (A) (*white dotted ovals*), prolonged cracks shown on (C) after sterilization (*white arrows*).

a double-scan strategy reported increased displacement of implants with SLA 3D-printed in comparison with milled templates.[18] However, the printing material used in that study has not been approved for the production of surgical guides, and information about the nesting, postprocessing, and print settings for the printed group was lacking. Both the SLA and DLP technique build the surgical template by polymerizing a photosensitive resin layer by layer. The specific layer thickness determines the accuracy of the printing device. In the present study, all surgical guides were printed with a layer thickness of 50 μm to maintain high resolution and optimum fit.[22]

One of the tested resin materials, NextDent SG, can be used with 2 different printing devices (Rapidshape D20II, Form2). Except for the implant displacement at the crest using surgical guides without autoclaving, the material performed significantly better when printed with the DLP device. These differences are most likely attributable to the different wavelengths used for resin polymerization. Specifically, the NextDent SG resin has a maximum polymerization rate at a wavelength of 385 nm as specified by the manufacturer, whereas the DLP device Rapidshape D20II uses a wavelength of 385 nm and the SLA printing device uses 405 nm. The polymerization efficacy might be impaired because of the different wavelengths, increasing dimensional errors within the template.[23] Comparably poorer accuracy was also found for surgical guides processed with the SLA device Form2. These results are consistent with those of a previous study using the same device that also reported considerable displacement of the implant position both horizontally and vertically.[19]

Comparing the accuracy of the different implant guides tested in the present study, the material 3Delta Guide showed the best match between preoperative and postoperative implant positions. Therefore, the second part of the null hypothesis was rejected. Except for the 3Delta Guide, all implants were positioned short of the designated apical length, consistent with previous reports also showing vertical displacement toward the alveolar crest.[12,14,16] Different factors might be responsible for the vertical displacement of the implant, including the fit of the guide being adversely affected by the resin shrinkage or the fit between the guide components.[24]

During surgical implant placement, these materials closely contact the surgical site. Concurrently, the surgical guide is typically exposed to contamination with numerous potentially pathogenic microorganisms causing infection and impaired healing and implant osseointegration in the course of manufacturing.[11] To address this problem, preoperative disinfection with antiseptics, for example chlorhexidine, ethanol, or octenidine has been recommended.[11] Autoclave sterilization is preferred to disinfection with antiseptics, being much more effective in inactivating microorganisms.[9,10] Because autoclaving involves high temperatures of more than 134 °C, deformation of the resin material might occur.

Sterilization of surgical guides manufactured with the 3Delta Guide material did not affect the implant position in comparison with nonsterilized guides. However, the horizontal position at the crest and the vertical position of surgical guides made of the resin material NextDent SG in an SLA-printing device (Form2) were affected after sterilization. Therefore, the third hypothesis was partially rejected.

The ultrastructural analysis of surgical guides manufactured from NextDent SG with the Form2 device showed numerous irregularly shaped cracks on the surface, indicating that heat sterilization induced deformation of the material. These changes were not observed when polymerizing this material with the Rapidshape D20II device. Ultrastructural changes within the material can reduce the fracture resistance of the template and lead to dimensional changes that might result in inaccuracies of the final implant position.

Limitations of the present study included its in vitro design. Clinical accuracy may be affected by soft hard tissue interferences, saliva, blood, and patient movement. The model material also did not have the same physical properties as bone and tooth substance, which can lead to clinical changes in the seating of the guides, implant bed drilling, and insertion of the implant. Further studies are indicated on the common design and manufacturing variables of the guides to be able to provide guidelines that can help clinicians achieve more reproducible and predictable results in guided implantology. Clinical studies are needed to confirm the in vitro findings.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Three-dimensional printing of resin material is appropriate for the manufacturing of surgical implant guides.
2. The accuracy of implant placement using 3D-printed surgical guides is almost comparable with that achieved with milled surgical templates.
3. The manufacturing technology, printing device, and resin material affected the precision of 3D-printed surgical guides.
4. The displacement of implants when using 3D-printed surgical guides appears to be within a commonly accepted range of safety.

AUTHOR CONTRIBUTIONS

Kessler Andreas: Contributed to conception, design, data acquisition and interpretation, drafted and critically revised the manuscript, agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any parts of the work are appropriately investigated and resolved. Dosch, Maximilian: Contributed to acquisition and analysis, critically revised manuscript, final approval of the version to be published, agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any parts of the work are appropriately investigated and resolved. Reymus, Marcel: contributed to design, critically revised manuscript, final approval of the version to be published, agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any parts of the work are appropriately investigated and resolved. Folwaczny Matthias: Contributed to conception, design, analysis and interpretation and critically revised the manuscript, final approval of the version to be published, agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any parts of the work are appropriately investigated and resolved.

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