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RESEARCH AND EDUCATION

Accuracy, reproducibility, and dimensional stability of additively manufactured surgical templates

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ABSTRACT

Statement of problem. Additively manufactured surgical templates are commonly used for computer-guided implant placement. However, their accuracy, reproducibility, and dimensional stability have not been thoroughly investigated with the different 3D printers and materials used for their fabrication.

Purpose. The purpose of this in vitro study was to evaluate the accuracy, reproducibility, and dimensional stability of additively manufactured surgical templates fabricated by using different 3D printers.

Material and methods. Thirty surgical templates were designed and additively manufactured from 3 different 3D printers as follows: group SLA (n=10) was fabricated by using a desktop stereolithography (SLA) 3D printer and photopolymerizing resin; group PolyJet (n=10) was fabricated by using a PolyJet 3D printer and photopolymerizing resins; and group DMP (n=10) was fabricated by using a direct metal printing (DMP) system and Co-Cr metal alloy. All surgical templates were scanned by using a laser scanner within 36 hours of production and digitalized again 1 month later. All scanned files were compared with the corresponding designed files in a surface matching software program. The mean deviation root mean square (RMS, measured in mm, representing accuracy), percentage of measurement data points within 1 standard deviation of mean RMS (in %, representing reproducibility), and dimensional changes were determined and compared.

Results. At the postproduction stage, group PolyJet was most accurate with the lowest RMS value of 0.10 ±0.02 mm and highest reproducibility with 93.07 ±1.54% of measurement data points within 1 standard deviation of mean RMS. After 1-month storage, group $\text{PolyJet}_{(1\text{month})}$ remained the most accurate with the lowest RMS value of 0.14 ±0.03 mm and the highest reproducibility value of 92.46 ±1.50%. For dimensional stability, group SLA versus group $\text{SLA}_{(1\text{month})}$ comparison showed a significant decrease in accuracy (RMS values of 0.20 ±0.08 mm versus 0.25 ±0.08 mm, $P<.001$) and reproducibility (88.16 ±3.66% versus 86.10 ±4.16%, $P=.012$). Group PolyJet versus group $\text{PolyJet}_{(1\text{month})}$ comparison only showed significant changes in accuracy (RMS values of 0.10 ±0.02 mm versus 0.14 ±0.03 mm, $P=.011$). Group DMP versus group $\text{DMP}_{(1\text{month})}$ comparison showed no significant changes in accuracy (RMS values of 0.19 ±0.03 mm versus 0.20 ±0.04 mm, $P=.981$) or reproducibility (89.77 ±1.61% versus 89.74 ±2.24%, $P=1.000$).

Conclusions. Printed resin surgical templates produced by using the PolyJet 3D printer showed higher accuracy and reproducibility than those produced by using the desktop SLA 3D printer and printed Co-Cr surgical templates at both the postproduction stage and after 1-month storage. The level of accuracy and reproducibility in printed Co-Cr surgical templates was not affected by 1-month storage. (J Prosthet Dent 2019;122:309-14)

Optimal dental implant placement can lead to simplified prosthetic procedures, esthetic outcomes, and long-term stability of peri-implant hard and soft tissues.[1] Inaccuracy during implant placement may occur because of limited mouth opening, asymmetric density of bone, and a clinician's lack of experience, causing deviations of the implant position.[2] Therefore, dental implant surgery should be carefully planned and

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Clinical Implications

All 3 chosen additive manufacturing technology and material combinations used in this study produce accurate and reproducible surgical templates, and the differences may not be of clinical significance, provided they are used within 36 hours of fabrication.

accurately executed to attain ideal 3D implant positioning.

With the advancement of cone beam computed tomography (CBCT), surface scanners, dental implant/craniofacial surgery-planning software, and computer-aided design and computer-aided manufacturing (CAD-CAM) technology, a digital treatment workflow can be used for computer-guided dental implant surgery. The Data Imaging and Communications in Medicine (DICOM) files generated by CBCT imaging and standard tessellation language (STL) files generated by surface scanners can be superimposed in the CAD-CAM and surgery-planning software. The merged data set allows the simultaneous and detailed viewing of the remaining dentition, the intraoral soft tissue, the underlying craniofacial hard tissue, and the virtual design of planned dental prosthesis.[3,4] A prosthetically driven implant-placement concept can then be used in computer-guided surgery planning, and the CAD-CAM surgical template and/or interim restoration can be designed and manufactured subtractively (milled) or additively (printed).[4-10]

The accuracy of computer-guided implant placement has been investigated.[11-15] Most studies have assessed accuracy by comparing the 3D positions of planned and placed implants in terms of the linear deviations of the implant head and apex and the angular deviations of the implant long axis.[4,16-18] Postoperative CBCT imaging are performed, and the preoperative and postoperative DICOM files are superimposed in the virtual implant planning software to determine the linear and angular deviations between planned and placed implants.[17-19] Reverse engineering techniques have also been used to assess accuracy.[20] Among these studies, only a few have focused on the accuracy and reproducibility of the surgical guide itself and its influence on the total accuracy.

Currently, surgical templates for computer-guided implant surgery are often produced by an additive manufacturing process (commonly referred to as 3D printing).[17] Additive manufacturing technology has become more popular as an alternative to subtractive manufacturing technology (milling) and as a less wasteful and more energy-efficient process.[21] Smaller and more economical desktop printers are available for additively manufacturing surgical templates in the clinic.[21,22] In previous studies, photopolymerizing resin was most frequently used to fabricate additively manufactured surgical templates.[22,23] Advancement in the additive manufacturing process and compatible metal alloys has made it possible to fabricate laser-sintered cobalt-chromium (Co-Cr) fixed dental prostheses and partial removable dental prosthesis frameworks with great accuracy.[24-26] This advancement suggests the possibility of producing additively manufactured Co-Cr surgical templates with greater strength and rigidity than those fabricated with photopolymerizing resin.

The present study evaluated the accuracy, reproducibility, and stability of CAD-CAM implant surgical templates fabricated by 3 different additive manufacturing processes and materials. The null hypotheses were that the accuracy, reproducibility, and stability of CAD-CAM surgical templates would not be affected by different additive manufacturing technology and material combinations.

MATERIAL AND METHODS

Central incisors, lateral incisors, and canines were removed from a maxillary typodont model (Prosthetic Restoration Jaw Model; Nissin Dental Products Inc), and the socket spaces were filled with polyvinyl siloxane putty impression material (Virtual Putty Fast; Ivoclar Vivadent AG) to simulate a partially edentulous clinical scenario. The simulated partially edentulous model was used as the master study cast and was scanned by using a laboratory laser scanner (7Series Model and Impression Scanner; Dental Wings Inc). The virtual master study cast was saved in STL format. The master study cast was also scanned by using a CBCT scanner (3D Accuitomo 170; J. Morita Corp) under the setting of fields of view at 80×80 mm, 75 kV, and 2.0 mA, and the scanned data were saved in the DICOM file format.

Implant planning and the designs of CAD-CAM implant surgical templates were performed in a virtual implant planning software (coDiagnostiX 9; Dental Wings Inc). STL files of the virtual master study cast and diagnostic waxing were superimposed with the DICOM data sets in the virtual implant planning software. Four virtual bone level implants (Bone Level Regular CrossFit 4.1×10 mm; Institut Straumann AG) were used for the planning purpose. CAD-CAM surgical templates were designed to be supported by the bilateral first molars, first and second premolars, and inspection windows on the buccal cusps of bilateral first molars and first premolars. A different material thickness was planned for the resin (3 mm) and metal (1 mm) surgical templates, according to manufacturers' recommendations (Fig. 1). Ten resin and 10 metal CAD-CAM surgical templates were designed individually and exported as STL files. All the

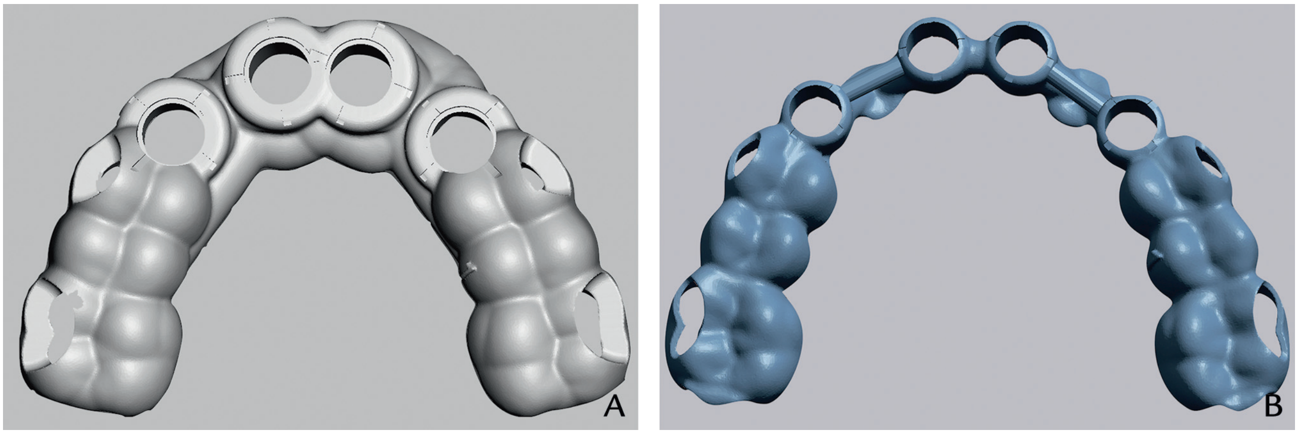

Figure 1. Representative designs of additively manufactured surgical templates. A, Design for SLA and PolyJet for production of resin surgical templates. B, Design for DMP for production of Co-Cr metal surgical templates. DMP, direct metal printing; SLA, stereolithography.

STL files were labeled with material type and number for ease of future identification.

Three different additive manufacturing technology were chosen in this study. The group SLA included a desktop stereolithography (SLA) 3D printer (Form 2; Formlabs Inc) and compatible photopolymerizing resin (Dental SG Resin; Formlabs Inc) and was produced in the authors' institution. The group PolyJet included a laboratory-based PolyJet 3D printer (Objet Eden260VS; Stratasys Ltd) and compatible photopolymerizing resin (MED610; Stratasys Ltd), and was outsourced to a commercial dental laboratory (Coredent Advancements LLC). The group DMP included a laboratory-based direct metal printing (DMP) system (ProX DMP 200; 3D Systems Inc) and Co-Cr metal alloy (LaserForm Co-Cr (C); 3D Systems Inc), and was outsourced to a commercial dental laboratory (3DRPD USA Inc). Ten resin surgical template STL files were used in both group SLA and group PolyJet to produce 10 resin templates from each group. Ten metal surgical template STL files were used in the group DMP to produce 10 metal templates. All additively manufactured resin (group SLA: n=10 and Group PolyJet: n=10) and metal (group DMP: n=10) CAD-CAM surgical templates were fabricated and processed according to the additive manufacturers' recommendations.

Trial insertions were completed for all CAD-CAM surgical templates on the master study cast to ensure there were no gross misfits of the templates. With the 36-hour postproduction time frame, the intaglio surfaces of all 30 surgical templates were lightly coated with antiglare spray (Helling 3D Scan Spray; CyberOptics Corp)[27] with an average particle size of 2.8 μm and then digitalized by using a laboratory laser scanner (7Series). The scanned files were saved in the STL file format and labeled accordingly with the group name and design file number for ease of future identification. All surgical templates were put in sealed plastic bags, then in a box, and then stored in the air-conditioned laboratory. All surgical templates were digitalized again after 1-month storage (simulating the possible time period between production of the surgical templates and a patient receiving computer-guided surgery), following the same protocol. The scanned files were labeled accordingly.

All scanned STL files of surgical templates were superimposed on the corresponding design STL files using best-fit alignment in the surface matching software (Geomagic Control X; 3D Systems Inc). After the automatic best-fit alignment in the surface matching software, the dimensional differences between the scanned surgical template and the corresponding design STL file were computed in the software. The mean deviation root mean square (RMS, measured in mm, absolute value) was used to represent overall accuracy, which estimated the congruency of 2 superimposed virtual files.[28] The percentage of measurement data points within 1 standard deviation of mean RMS was used to represent reproducibility.[29]

To determine differences in accuracy (RMS, measured in mm) and reproducibility (percentage of measurement data points within 1 standard deviation of mean RMS values) at postproduction and after 1-month storage, the repeated-measures ANOVA and post hoc tests were used, with each group and time having different variances. A statistical software program (SAS version 9.4; SAS Institute Inc) was used for all statistical analyses (α=.05).

RESULTS

All null hypotheses were rejected based on the statistical analysis of the results, confirming that different additive manufacturing technology and material combinations affected the accuracy, reproducibility, and stability of the CAD-CAM surgical templates. Color maps of the surface matching differences for each group are shown in

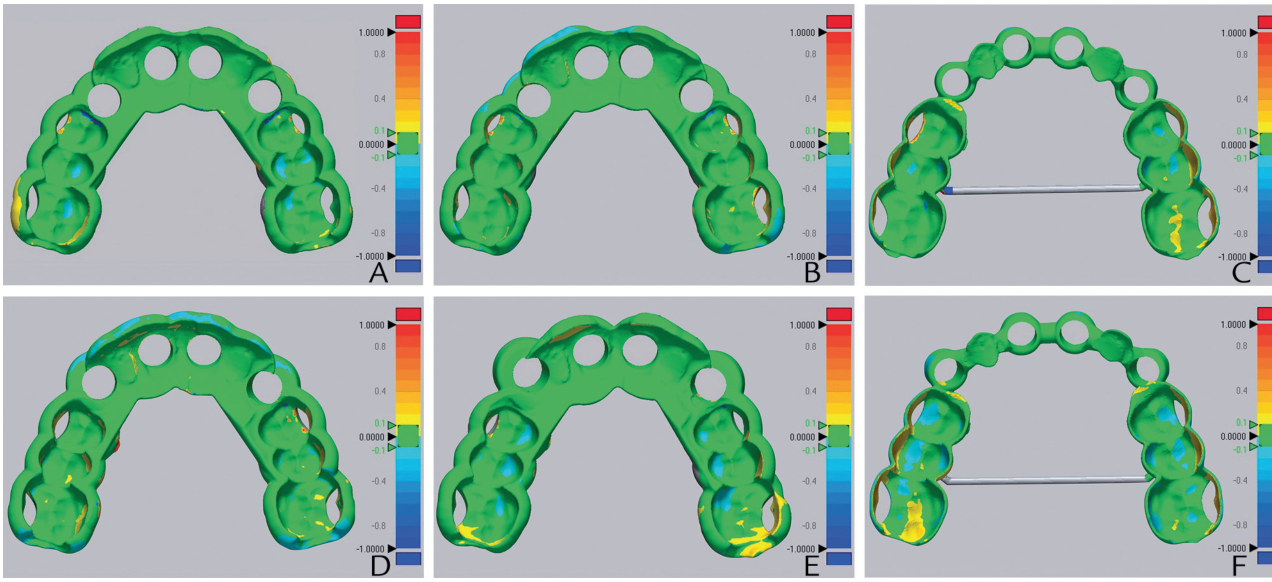

Figure 2. Representative surface matching color maps from 6 study groups. A, SLA immediately. B, PolyJet immediately. C, DMP immediately. D, SLA at 1 month. E, PolyJet at 1 month. F, DMP at 1 month. DMP, direct metal printing; SLA, stereolithography.

Figure 2. Most of the areas are green in color, indicating surface matching within ±0.1 mm. Areas in blue (negative discrepancies) indicate a smaller surgical template when compared with the corresponding design STL file. Areas in yellow and red (positive discrepancies) indicate a larger surgical template when compared with the corresponding design STL file.

The accuracy and reproducibility of the CAD-CAM surgical templates immediately after production and after 1-month storage are shown in Table 1. Immediately after production, the PolyJet group had a significantly lower RMS value (0.10 ±0.02 mm) than SLA (0.20 ±0.08 mm, P=.012) or DMP (0.19 ±0.03 mm, P<.001). Similarly, the PolyJet group had significantly better performance in reproducibility, with 93.07 ±1.54% of measurement data points within 1 standard deviation of mean RMS values, than SLA (88.12 ±3.66%, P=.008) or DMP (89.77 ±1.61%, P=.002). After 1-month storage, the PolyJet group still had a significantly lower RMS value (0.14 ±0.03 mm) than SLA (0.25 ±0.08 mm, P=.005) or DMP (0.20 ±0.04 mm, P=.025). Similarly, the PolyJet group still had significantly better reproducibility (92.46 ±1.50%) than SLA (86.10 ±4.16%, P=.003) or DMP (89.74 ±2.24%, P=.038). To test the dimensional stability of surgical templates fabricated with 3 different additive manufacturing technology and material combinations, the accuracy and reproducibility comparisons were made between the postproduction stage and after 1-month storage for each corresponding group pair. After 1-month storage, RMS values increased significantly in the SLA and PolyJet group comparison (P<.001 and P=.011, respectively). RMS values remained similar (P=.981) in the DMP group. For the performance in reproducibility, only SLA showed a significant decrease in the percentage of measurement data points within 1 standard deviation of mean RMS values after 1-month storage (P=.012). The reproducibility did not show any differences for PolyJet or DMP after 1-month storage (P=.829 and P=1.000, respectively).

DISCUSSION

All null hypotheses were rejected, confirming that different additive manufacturing technology and material combinations did affect the accuracy, reproducibility, and stability of the CAD-CAM surgical templates. In the clinical scenario, the accuracy of computer-guided implant placement is affected by multiple factors, including the quality of diagnostic radiographic imaging and the radiographic template, the accuracy of the digital cast produced by intraoral scanning or extraoral scanning, the accuracy of the surgical template and its stable fit on supporting tissue, and the surgeon's execution of the planned surgery.[11] Other factors such as the fabrication procedure of the surgical template (subtractive versus additive manufacturing),[5] types of sleeve inserts,[14] and wear of sleeves and surgical drills[15] can also affect the accuracy of guided surgery. Future studies can be designed to improve the accuracy of computer-guided surgery.

In the present study, an evaluation protocol was used that focused on the 3D congruency between the reference design and additively manufactured surgical templates. Antiglare spray (Helling 3D Scan Spray) with

Table 1. Accuracy and reproducibility of additively manufactured surgical templates immediately after production and after 1-month storage

RMS (mm ±Standard Deviation) Representation of Accuracy				Percentage of Measurement Data Points Within 1 Standard Deviation of Mean RMS Values (% ±Standard Deviation) Representation of Reproducibility			
Group SLA	0.20 ±0.08[a]	Group $SLA_{(1month)}$	0.25 ±0.08[a]	Group SLA	88.16 ±3.66[a]	Group $SLA_{(1month)}$	86.10 ±4.16[a]
Group PolyJet	0.10 ±0.02[b]	Group $PolyJet_{(1month)}$	0.14 ±0.03[b]	Group PolyJet	93.07 ±1.54[b*]	Group $PolyJet_{(1month)}$	92.46 ±1.50[b*]
Group DMP	0.19 ±0.03[a*]	Group $DMP_{(1month)}$	0.20 ±0.04[a*]	Group DMP	89.77 ±1.61[a*]	Group $DMP_{(1month)}$	89.74 ±2.24[a*]

DMP, direct metal printing; RMS, root mean square; SLA, stereolithography. Accuracy and reproducibility with same letter in same column not statistically different, *P*>.05. Accuracy and reproducibility with * in same row not statistically different, *P*>.05.

minimal material thickness was used in all the scanning procedures in conjunction with a laboratory-based laser scanner with 15-μm scanning accuracy to improve the consistency of scanning results.[27] With the selected surface matching software (Geomagic Control X), several parameters such as RMS and deviation distribution can be calculated.[28] RMS was used as an indicator of the absolute magnitude of deviation between 2 different 3D data sets and as an indicator of accuracy in this study. The lower the RMS, the higher the 3D congruency of 2 superimposed files and the higher the accuracy of surgical templates produced from the corresponding design file. The percentage of measurement data points within 1 standard deviation of mean RMS values represents the reproducibility of the fabrication process. The higher percentage represents a more reproducible printing procedure with consistent reproduction results from the design file.[29]

In the printed resin surgical templates groups, the templates produced by using the laboratory-based PolyJet 3D printer were more accurate and reproducible than those produced by using the desktop SLA 3D printer immediately after production. These differences persisted after 1-month storage. The higher accuracy and reproducibility of printed resin surgical templates from the PolyJet 3D printer may be explained by the better printing resolution and smaller printing layer thickness of this industrial-level 3D printer than those of the desktop SLA 3D printer. All resin surgical templates produced by using the laboratory-based PolyJet and desktop SLA 3D printers showed decreased accuracy after 1-month storage. Based on the manufacturers' recommendation, although the PolyJet 3D printing technology does not require a postproduction polymerization, the desktop SLA 3D printer requires the additional postproduction polymerization of printed resin surgical templates to promote the complete polymerization of the residual resin initiator and improve the accuracy and stability.[23] The findings of the present study show that the 1-month storage decreased the accuracy of all resin surgical templates. The dimensional stability of the printed surgical templates from the laboratory-based PolyJet and desktop SLA 3D printers may require further investigation.

The accuracy of Co-Cr metal surgical templates may be attributed to the DMP technology that is used to produce fully dense objects and the possibility that porosity in the printed surgical templates is low. According to the manufacturer, the high surface finish quality of up to 5 Ra μm on the printed object could be realized when the Co-Cr powder has a fine average particle size of 16 μm. In addition, laboratory-based heat-treatment procedures should be considered with printed Co-Cr metal surgical templates to relieve the embedded energy after additive manufacturing and prevent deformation.[26] In this current research, a proprietary heat-treatment process was developed by the dental laboratory (3DRPD USA Inc) for fabricating printed Co-Cr metal surgical templates. Under the short-term 1-month storage condition, printed Co-Cr metal surgical templates produced by using the DMP 3D printer retained their accuracy and reproducibility. Although the production cost for the DMP 3D printed Co-Cr metal surgical template is higher than that for the printed resin, the present study shows that it might be indicated where prolonged storage of a surgical template is required.

Although statistically significant differences were found in this study, the absolute values of all dimensional differences were small and may not cause any clinically significant effects. This study also demonstrated that an economic desktop SLA 3D printer may be appropriate for producing surgical templates in dental offices. However, future clinically controlled trials should be conducted to further investigate the applications of various additive manufacturing technologies and material combinations in implant dentistry and their cost-effectiveness on the outcomes of computer-guided implant surgery.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Printed resin surgical templates produced by using the laboratory-based PolyJet 3D printer show higher accuracy and reproducibility than those produced by the more economic desktop SLA 3D printer, and these differences persist after 1-month storage.
2. Printed resin surgical templates produced by using the laboratory-based PolyJet 3D printer and desktop SLA 3D printer show diminished accuracy after 1-month storage. Printed Co-Cr metal surgical templates produced by using the DMP 3D printer retain

their initial accuracy and reproducibility after 1-month storage.

3. All 3 chosen additive manufacturing technology and material combinations produce accurate and reproducible surgical templates. Although the differences may not be clinically significant, this must be evaluated in clinical studies.

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