journal of the mechanical behavior of biomedical materials 152 (2024) 106418

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Accuracy of additively manufactured and steam sterilized surgical guides by means of continuous liquid interface production, stereolithography, digital light processing, and fused filament fabrication

Felix Burkhardt [a,*], Leon Handermann [a], Severin Rothlauf [a], Aiste Gintaute [a], Kirstin Vach [b], Benedikt C. Spies [a], Jörg Lüchtenborg [a]

[a] Medical Center – University of Freiburg, Center for Dental Medicine, Department of Prosthetic Dentistry, Faculty of Medicine, University of Freiburg, Hugstetter Str. 55, 79106, Freiburg, Germany

[b] Medical Center - University of Freiburg, Institute of Medical Biometry and Statistics, Faculty of Medicine, University of Freiburg, Stefan-Meier-Str. 26, 79104, Freiburg, Germany

A R T I C L E I N F O

Keywords:
Digital light synthesis
Continuous liquid interface production
Additive manufacturing
Medical 3D printing
Fused filament fabrication
Steam sterilization
Surgical guides

A B S T R A C T

Different printing technologies can be used for prosthetically oriented implant placement, however the influence of different printing orientations and steam sterilization remains unclear. In particular, no data is available for the novel technology Continuous Liquid Interface Production. The objective was to evaluate the dimensional accuracy of surgical guides manufactured with different printing techniques in vertical and horizontal printing orientation before and after steam sterilization. A total of 80 surgical guides were manufactured by means of continuous liquid interface production (CLIP; material: Keyguide, Keyprint), digital light processing (DLP; material: Luxaprint Ortho, DMG), stereolithography (SLA; Surgical guide, Formlabs), and fused filament fabrication (FFF; material: Clear Base Support, Arfona) in vertical and horizontal printing orientation ($n = 10$ per subgroup). Spheres were included in the design to determine the coordinates of 17 reference points. Each specimen was digitized with a laboratory scanner after additive manufacturing (AM) and after steam sterilization (134 °C). To determine the accuracy, root mean square values (RMS) were calculated and coordinates of the reference points were recorded. Based on the measured coordinates, deviations of the reference points and relevant distances were calculated. Paired t-tests and one-way ANOVA were applied for statistical analysis (significance $p < 0.05$). After AM, all printing technologies showed comparable high accuracy, with an increased deviation in z-axis when printed horizontally. After sterilization, FFF printed surgical guides showed distinct warpage. The other subgroups showed no significant differences regarding the RMS of the corpus after steam sterilization ($p > 0.05$). Regarding reference points and distances, CLIP showed larger deviations compared to SLA in both printing orientations after steam sterilization, while DLP manufactured guides were the most dimensionally stable. In conclusion, the different printing technologies and orientations had little effect on the manufacturing accuracy of the surgical guides before sterilization. However, after sterilization, FFF surgical guides exhibited significant deformation making their clinical use impossible. CLIP showed larger deformations due to steam sterilization than the other photopolymerizing techniques, however, discrepancies may be considered within the range of clinical acceptance. The influence on the implant position remains to be evaluated.

1. Introduction

Surgical guides are used for statically navigated oral implant positioning based on prosthetically oriented backward planning in a digital workflow (Pozzi et al., 2016). As a result, the risk of implant malposition can be significantly reduced and consequently biological and technical complications can be minimized (Fretwurst et al., 2018; Lo Russo et al., 2023). Apart from a possible fabrication of the surgical guides in a milling process (Chai et al., 2020), additive manufacturing (AM) represents the gold standard, as it leads to reduced material wastage and low equipment wear (Ahmad et al., 2022; Revilla-León et al., 2020). AM is based on a computer-aided design (CAD) of the surgical guide, which

* Corresponding author.
E-mail address: felix.burkhardt@uniklinik-freiburg.de (F. Burkhardt).

https://doi.org/10.1016/j.jmbbm.2024.106418
Received 6 December 2023; Received in revised form 16 January 2024; Accepted 23 January 2024
Available online 24 January 2024

is transformed into a three-dimensional object in a layerwise printing process. In daily practice, surgical guides are most commonly fabricated from resin-based materials using vat photopolymerization such as stereolithography (SLA) or digital light processing (DLP) (Piedra-Cascón et al., 2021; Revilla-León et al., 2020). In the SLA process, an ultraviolet (UV) laser beam is directed at photocurable resin, which is applied in layers to a build platform, curing the object to be printed (Calignano et al., 2017; Taormina et al., 2018). The DLP process uses an UV light projector instead of a spot laser, allowing an entire printing layer to be cured at once. Thus, the printing speed of the DLP process is independent of the area of the sliced parts in the individual layers and can be increased compared to SLA (Ligon et al., 2017). These two processes allow the manufacturing of patient-specific, complex geometries with a high degree of precision (Quan et al., 2020).

Fused filament fabrication (FFF) is a monomer-free printing technology (Aimar et al., 2019; Crump, 1992). In this cost-effective and straight-forward method, a thermoplastic filament is melted and the resulting object is built layer by layer, requiring only minimal post-processing (Burkhardt et al., 2020; Ngo et al., 2018). FFF is increasingly used in the dental sector for laboratory or clinical auxiliary devices such as dental models or individual impression trays (Lüchtenborg et al., 2021). Furthermore, the utilization of FFF in the manufacturing of surgical guides has witnessed a notable surge (Gielisch et al., 2023; Pieralli et al., 2020). Consequently, filaments tailored for this specific application are already accessible in the commercial marketplace. However, the described processes are associated with limitations such as a long production times (Ngo et al., 2018), possible warpage (Schirmeister et al., 2021; Spoerk et al., 2017), and potential difficulties regarding the sterilization process.

Another novel AM technique, termed continuous liquid interface production (CLIP) or digital light synthesis (DLS), was recently developed by Carbon (Tumbleston et al., 2015). In contrast to the SLA or DLP process, oxygen continuously diffuses through a permeable window at the bottom of the tank (Janusziewicz et al., 2016). Due to the known phenomenon of oxygen inhibition, a region of unpolymerized resin, also called dead zone, is formed in this area (Tumbleston et al., 2015). This enables continuous AM, which eliminates the incremental layer-by-layer approach. This is reflected in a comparatively smooth, non-layered surface structure which enables the precise production of fine structures (Janusziewicz et al., 2020; Johnson et al., 2016). Due to the rapid printing speed of up to 100 mm/h, large scale production seems feasible (Tumbleston et al., 2015). The resulting oxygen inhibition layer inactivates free radicals at the interface between the polymer and the tank and prevents adhesion of the printing object to the bottom of the tank (Janusziewicz et al., 2016). Consequently, mechanical delamination is not necessary, whereby forces on the partially polymerized objects can be avoided.

For the established printing processes such as SLA, an influence of the printing orientation on the printing accuracy could be observed (Dalal et al., 2020; Diken Turksayar et al., 2022; Nold et al., 2021; Unkovskiy et al., 2018). Little is known about how this is reflected in objects made with the novel CLIP technology, as they should exhibit a smooth and layer-free surface compared to the other techniques. However, it remains unclear how objects manufactured with this new technology behave regarding their dimensional accuracy during steam sterilization (Keβler et al., 2022). The influence of different sterilization techniques on SLA and DLP printed surgical guides was investigated in recent studies (Chan et al., 2021; Pop et al., 2022). Depending on the sterilization process and the printing technology, an effect on the deformation (Chan et al., 2021) and mechanical properties (Pop et al., 2022) was observed. With regard to FFF printing, it is reported that heat-based sterilization methods are not recommended for the thermoplastic filaments (Told et al., 2022), although other studies describe dimensionally accurate sterilization for example at 121 °C steam sterilization (Pieralli et al., 2020; Rothlauf et al., 2023).

In addition to accurate AM, it is essential that surgical guides can be sterilized in a dimensionally stable manner prior to their use in the surgical field (Sharma et al., 2020; Told et al., 2022). Therefore, this study aimed to investigate the influence of printing orientation (horizontal, vertical) as well as steam sterilization on the trueness and precision of surgical guides. For this purpose, surgical guides manufactured using the novel CLIP technique were compared to the vat photopolymerization methods DLP and SLA as well as the extrusion-based technique FFF. The null hypothesis assumed no differences between the groups in both printing orientations regarding dimensional accuracy after AM and steam sterilization.

2. Materials and methods

2.1. Digital implant planning

A lower jaw typodont model (X-1072, Nissin, Kyoto, Japan) with the missing teeth 34–36 (according to FDI notation) was used for the planning of an implant-supported fixed dental prostheses. To simulate a clinical workflow, cone-beam tomography (CBCT; Morita Accuimoto 170, J. Morita, Kyoto, Japan) of the model was performed and surface data were acquired using an intraoral scanner (Trios 4, 3Shape, Copenhagen, Denmark). The respective datasets (Digital Imaging and Communications in Medicine, DICOM; standard tessellation language, STL) were imported into an implant planning software (SMOP, Swissmeda AG, Baar, Switzerland). In addition, a digitized wax-up simulating the prospective prosthetic restoration was used to plan the implant positions in terms of backward planning. Based on this, the insertion of two parallel implants (Screw Line Promote Plus, Camlog, Basel, Switzerland) with a diameter of 4.3 mm was planned. The design of the surgical guide was created in the implant planning software (SMOP) and the exported STL was completed with 17 hemispheres with a diameter of 5 mm serving as reference points (Fusion 360, Autodesk, San Rafael, USA).

2.2. Evaluated materials

Three different methacrylate-based resins for dental AM were investigated. The resin of the CLIP (Keyguide, Keyprint, Keystone Industries, New Jersey, USA) and SLA Group (Formlabs, Somerville, Massachusetts, USA) were both approved for the manufacturing of Class I medical devices, whereas Class IIa medical devices could be manufactured with the resin of the DLP Group (Luxaprint ortho, DMG, Hamburg, Germany). The polyethylene terephthalate (PETG) filament from the FFF Group (Clear Base Support Filament, Arfona, Englewood Cliffs, New Jersey, USA) was approved for the manufacturing of Class I medical devices.

2.3. Additive manufacturing of surgical guides

Four different printing methods were evaluated (CLIP, SLA, DLP, FFF), with one horizontal and one vertical printing orientation (80–90° to the printing platform) per group ($n = 10$ per subgroup). The printing parameters and details are shown in Table 1, and printed surgical guides are visualized in Fig. 1.

2.4. Steam sterilization

All surgical guides were steam sterilized after AM (Vaculav 40B+, Melag, Berlin, Germany) for 5 min and 30 s at 134 °C (2 bar).

2.5. Data acquisition

All surgical guides ($n = 80$) were digitized within one day after AM and after steam sterilization with a laboratory scanner (3Shape E4, 3Shape). For this purpose, the surgical guides were fixed in a custom-made additively manufactured fixture in order to capture the guide as completely as possible. This enabled the recording of both the fitting

Table 1
Details of printing technology, materials and setting.

Technology (Group)	Printer	Material	Printing Settings
CLIP	Carbon M2 (Carbon)	Keyguide (Keyprint)	Layer height: 0.1 mm Thickness basis: 1.5 mm Thickness wall: 0.6 mm
DLP	3Demax (DMG)	Luxaprint Ortho (DMG)	Layer height: 0.05 mm; Washing: 99 % Isopropanol (20 min) Light cure: 70 °C (30 min)
SLA	Form 3 (Formlabs)	Surgical Guide (Formlabs)	Layer height: 0.05 mm Washing: 99 % Isopropanol (20 min) Light cure: 70 °C (30 min)
FFF	Prusa Mini+ (Prusa)	Clear Base Support (Arfona)	Diameter filament: 1.75 mm Layer height: 0.05 mm Layer height (first layer): 0.1 mm; Nozzle diameter: 0.25 mm Shells: 3 Nozzle temperature: 240 °C Printing bed temp.: 70 °C Infill: 100 % Infill pattern: linear Printing speed: 20–30 mm/s

surface and the external surface of the surgical guide. Subsequently, all STL data sets were imported into an inspection software program (Geomagic Control X, 3D Systems, Rock Hill, South Carolina, USA). The data sets after AM and after steam sterilization were compared to the CAD file in order to determine deviations due to AM and additional steam sterilization. The scans were superimposed with the CAD file by means of a local best-fit algorithm according to Gauss. The hemispheres and the corpus of the surgical guide were evaluated separately. In addition, the area around the holder was omitted by the same extent for all data sets. The mean deviation in the area of the corpus of the surgical guides was determined using the Root Mean Square (RMS) value and the deviations were exemplarily visualized using a color map with a tolerance of ±50 μm. For the deviation of the reference points, the center of the hemisphere was automatically computed and the coordinates of the x-, y-, and z-axis exported. Finally, the deviation was calculated by subtracting the respective coordinates of the CAD file. Vectors indicating the extent of distortion were calculated. The distances a-e, shown in Fig. 2, were calculated after AM and after sterilization and were compared to the respective distances in the CAD file.

2.6. Statistical analysis

For descriptive analysis mean values and standard deviations (reported as mean ± SD) were calculated. For graphical presentation box plots were used. Linear regression models were applied to test RMS values for material differences after AM and after steam sterilization and for changes due to steam sterilization. Paired t-tests were performed to evaluate RMS differences before and after sterilization within each subgroup. To calculate the vector length indicating the deviation of the reference points after steam sterilization in comparison to the CAD file for each reference point, the square root of the sum of the squared

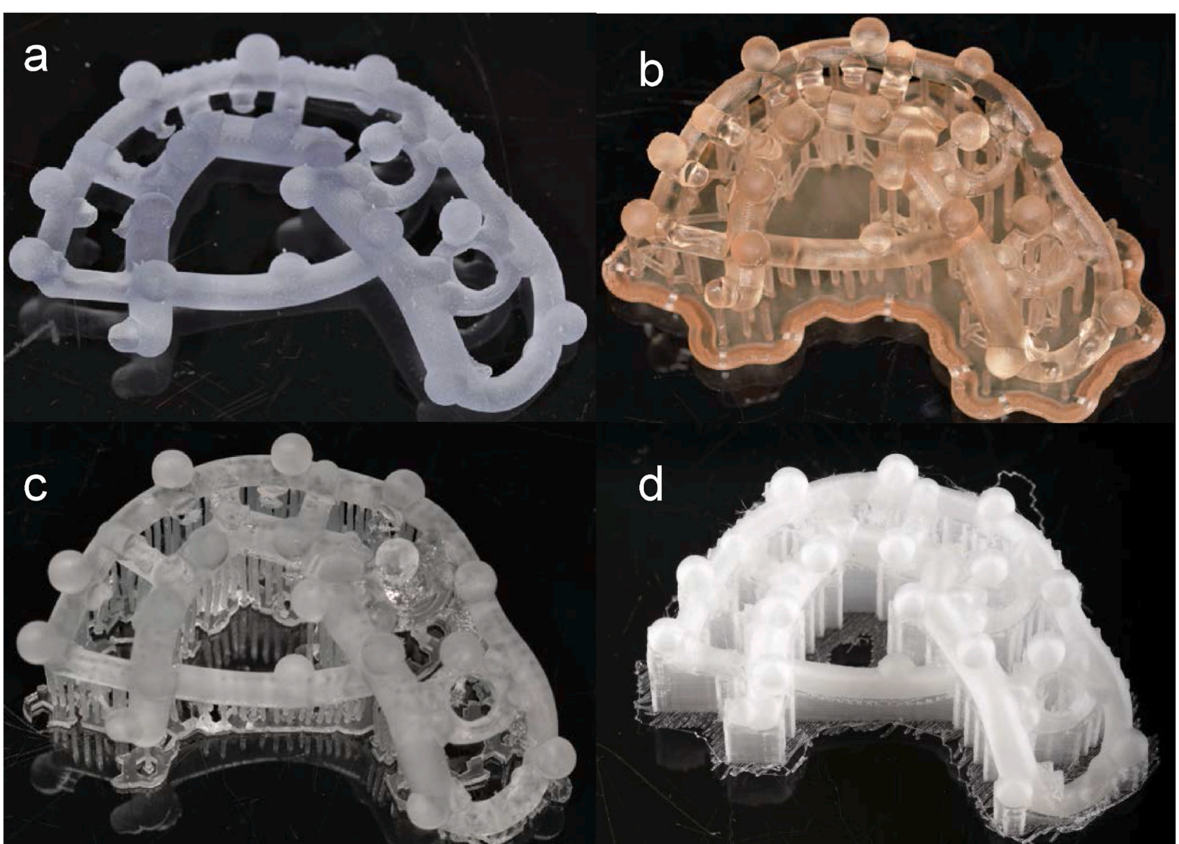

Fig. 1. Horizontally manufactured surgical guides by means of CLIP (a) after removal of support structures; SLA (b), DLP (c), and FFF (d) with support structures. *(color artwork)*.

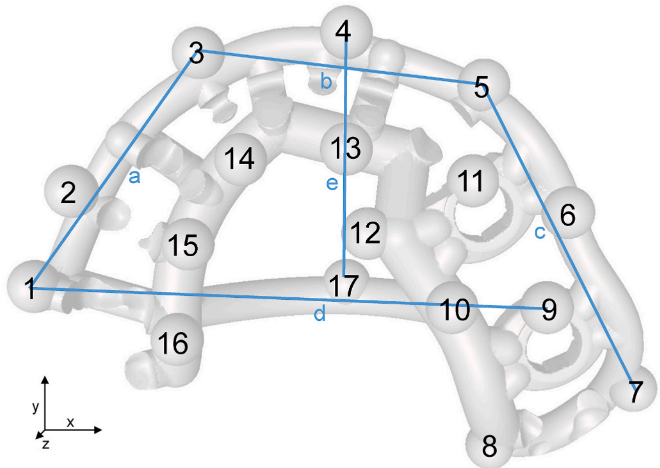

Fig. 2. STL of the surgical guide. Number of reference points (1–17) and evaluated distances between 1 and 3 (a); 3 and 5 (b); 5 and 7 (c); 1 and 9 (d); and 4 and 17 (e).

individual differences in x, y, and z direction to the CAD file was build. The same procedure was applied when computing differences in the prespecified distances a-e.

Paired t-tests were used to test for differences between pre and post sterilization per group and axis as well as for within-group differences. Material differences were tested using one-way-ANOVA, in case of subsequent pairwise comparisons the Student-Newman-Keuls's method was used to correct for multiple testing. The significance level was set to 0.05. All computations were done with STATA (Version 17.0, College Station, Texas, USA).

3. Results

All surgical guides were digitized after AM to evaluate the dimensional accuracy of the manufacturing process ($n = 80$). After steam sterilization, the FFF surgical guides showed distinctive deformations and warpage (Fig. 3), leading to the exclusion of this group for further evaluation. The remaining surgical guides ($n = 60$) were included for further evaluation after steam sterilization.

3.1. *Corpus of the surgical guide*

After AM, the corpus of the horizontally manufactured surgical guide using FFF (0.39 ± 0.16) and DLP in vertical orientation (0.39 ± 0.15) showed the lowest RMS, followed by the horizontal SLA (0.40 ± 0.26) and vertical FFF group (0.40 ± 0.34) (Fig. 4). The highest RMS was observed for the surgical guides of the vertical CLIP group (0.49 ± 0.13). After steam sterilization, the lowest RMS was calculated for the vertical SLA group (0.34 ± 0.16) and the highest for the horizontal CLIP group (0.46 ± 0.18). Both FFF subgroups showed by far the strongest dimensional change after steam sterilization, however, the RMS value was not calculated since a matching of the scans of the FFF groups was not possible. No significant differences were observed between DLP, SLA, and CLIP after AM and after steam sterilization ($p > 0.05$) and the changes due to steam sterilization within one group and between groups did not reach statistical significance ($p > 0.05$). Surface analysis showed increased warpage, particularly in the marginal areas of the CLIP and SLA surgical guides. The horizontally printed surgical guides of the DLP group showed a consistent positive deviation of approximately 200 µm (Fig. 5).

3.2. *Reference points*

The coordinates of the 17 reference points were measured after AM and after steam sterilization. A vector was calculated for each reference point, reaching from the coordinate points of the CAD file to the measured coordinates. Measured coordinates are shown in Fig. 6 and vector lengths, indicating the deviation from the CAD file, are shown in Fig. 7. Similar to the surface analysis of the corpus, CLIP surgical guides showed an increased deviation after steam sterilization. With both vertical and horizontal printing orientation, the CLIP surgical guides showed an increased deviation of the reference points 1–8, which were located in the marginal areas. In particular, the vertical printing orientation showed that the reference points were more central in the peripheral areas of the surgical guide (points 3, 4, 5, 7, 8) after sterilization. Similar to the surface analysis, both printing orientations of the DLP group revealed only minor changes of the reference points after steam sterilization. The SLA groups showed increased warpage in the left (point 1) and right peripheral areas (points 7, 8).

When calculating the total deviation of all reference points per subgroup (horizontal, vertical), the highest deviation was observed in z-axis for all horizontally printed groups after AM (Fig. 8). This was also apparent after steam sterilization, with the horizontal CLIP group in particular showing the strongest deviation in z-axis. In the vertical CLIP group, however, the strongest deviation was observed in y-axis before and after sterilization. When comparing the deviations per group and axis, significant changes ($p < 0.001$) were observed in x-, y-, and z-axis for the horizontal and vertical SLA group due to steam sterilization.

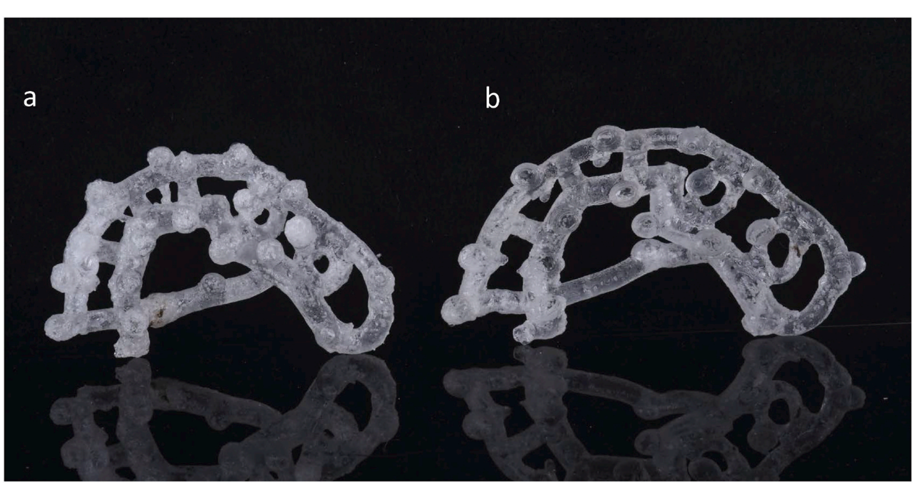

Fig. 3. Exemplary visualization of a horizontally (a) and vertically (b) manufactured FFF surgical guide after steam sterilization, both showing distinctive deformation. *(color artwork)*.

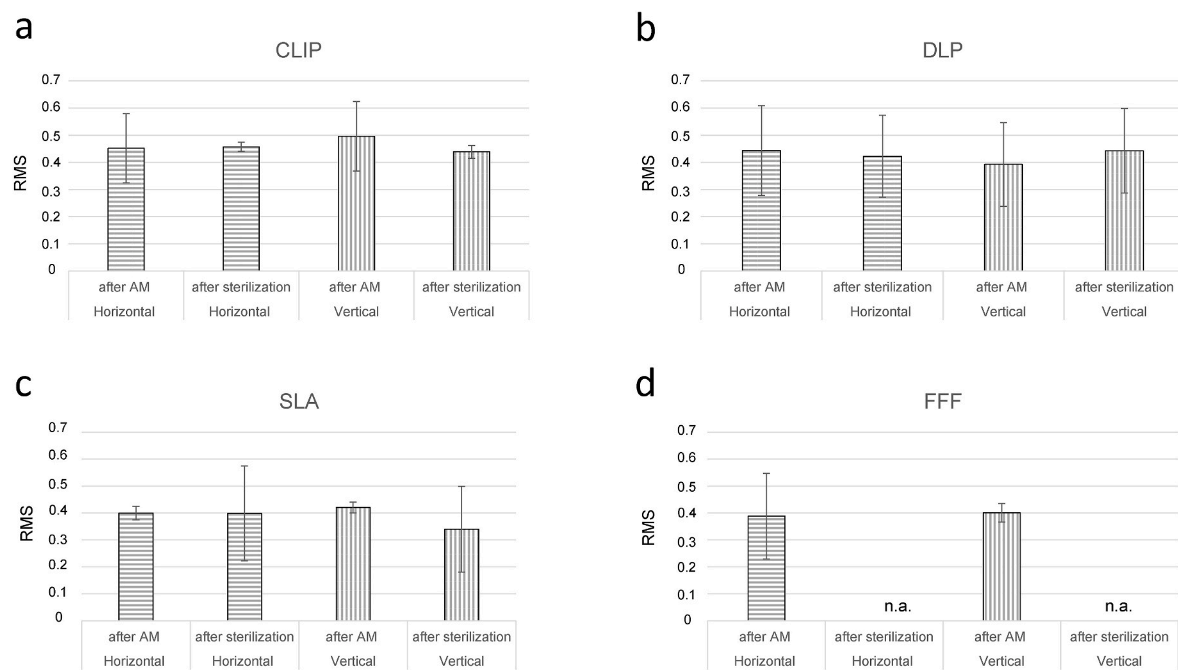

Fig. 4. RMS value of the corpus of the surgical guide after AM and after steam sterilization of the groups CLIP (a); DLP (b); SLA (c); and FFF (d).

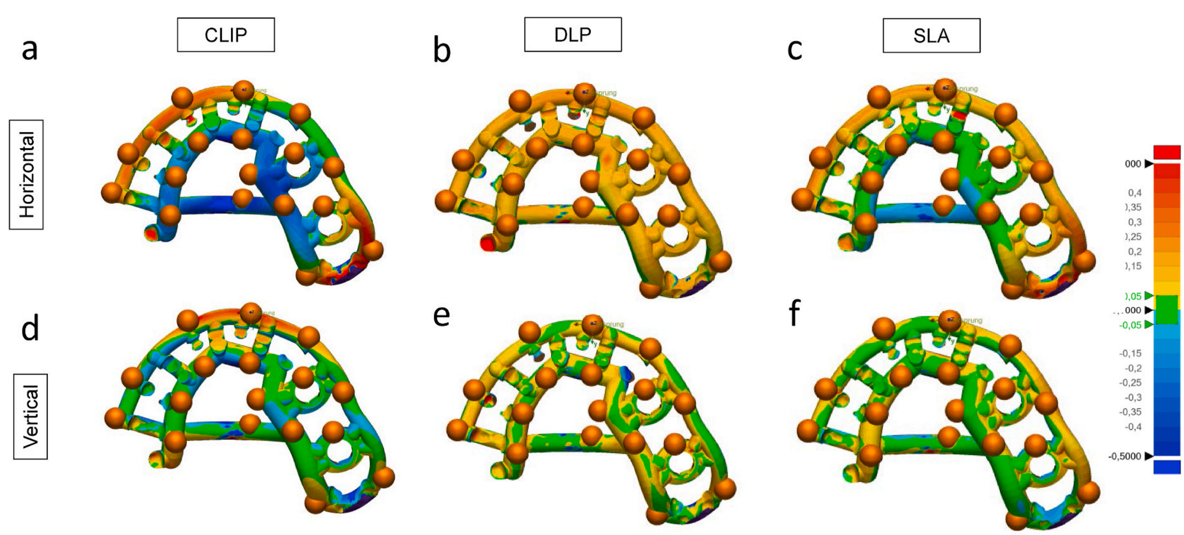

Fig. 5. Representative surface analysis of the surgical guides (tolerance of ±50 μm in green) manufactured by means of CLIP (a, d); DLP (b, e); and SLA (c, f) after steam sterilization. The upper row represents the horizontally printed surgical guides, the lower row the vertically printed surgical guides. Areas in blue (negative divergence) indicate a smaller surgical guide, while areas in yellow, orange, and red (positive divergence) indicate a larger surgical guide compared to the CAD file. *(color artwork)*.

While significant changes regarding x-, y-, and z-axes were observed by steam sterilization for CLIP in horizontal printing orientation ($p < 0.001$), changes were significant in vertical printing orientation only in x- and y-axis ($p < 0.01$), but not in z-axis ($p = 0.25$). The changes due to sterilization of the horizontal and vertical DLP groups were not significant, except for the x-axis when AM was performed in a vertical printing orientation ($p = 0.0021$).

3.3. Distances

When printed horizontally, the distances a and c, located longitudinally on the left and right side (Fig. 2), showed no significant differences from the CAD file ($p > 0.05$) (Fig. 9). After steam sterilization, a significantly longer distance was measured compared to the CAD file for both distances of all printing technologies ($p < 0.05$), with the exception of distance a for the horizontal CLIP group ($p = 0.37$). A high increase of the distances a and c was measured after AM for the vertical CLIP group compared to the CAD file, which increased further after sterilization. Considering the distances b and d, which were both located transversally, no changes to the CAD file ($p > 0.05$) or significantly shorter distances ($p < 0.05$) were measured for the CLIP and DLP technology regardless of the printing orientation (Fig. 9). The SLA technology, however, showed a significant increase of distance b after AM when printed horizontally ($p < 0.01$), whereas this distance in vertical printing orientation ($p = 0.48$) and distance d in both orientations (both $p > 0.50$) showed no significant differences to the CAD file. After sterilization, a significant increase was observed for both distances and printing orientations ($p < 0.01$), with the exception of distance d in horizontal

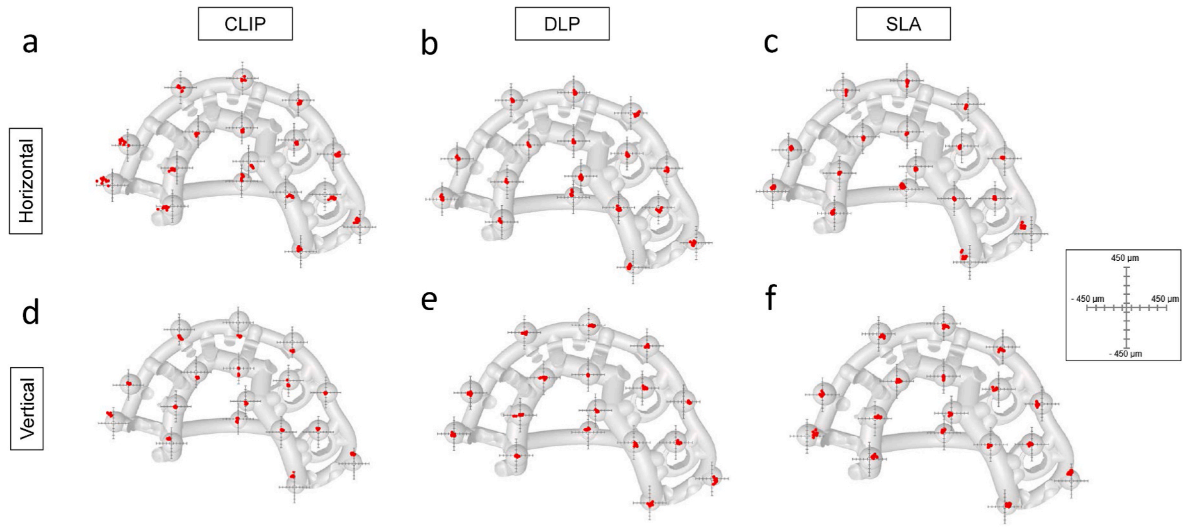

Fig. 6. Illustration of the measured coordinates (n = 10) of the 17 reference points after steam sterilization of group CLIP (a, d); DLP (b, e); and SLA (c, f). The upper row represents the horizontally printed surgical guides, the lower row the vertically printed surgical guides.

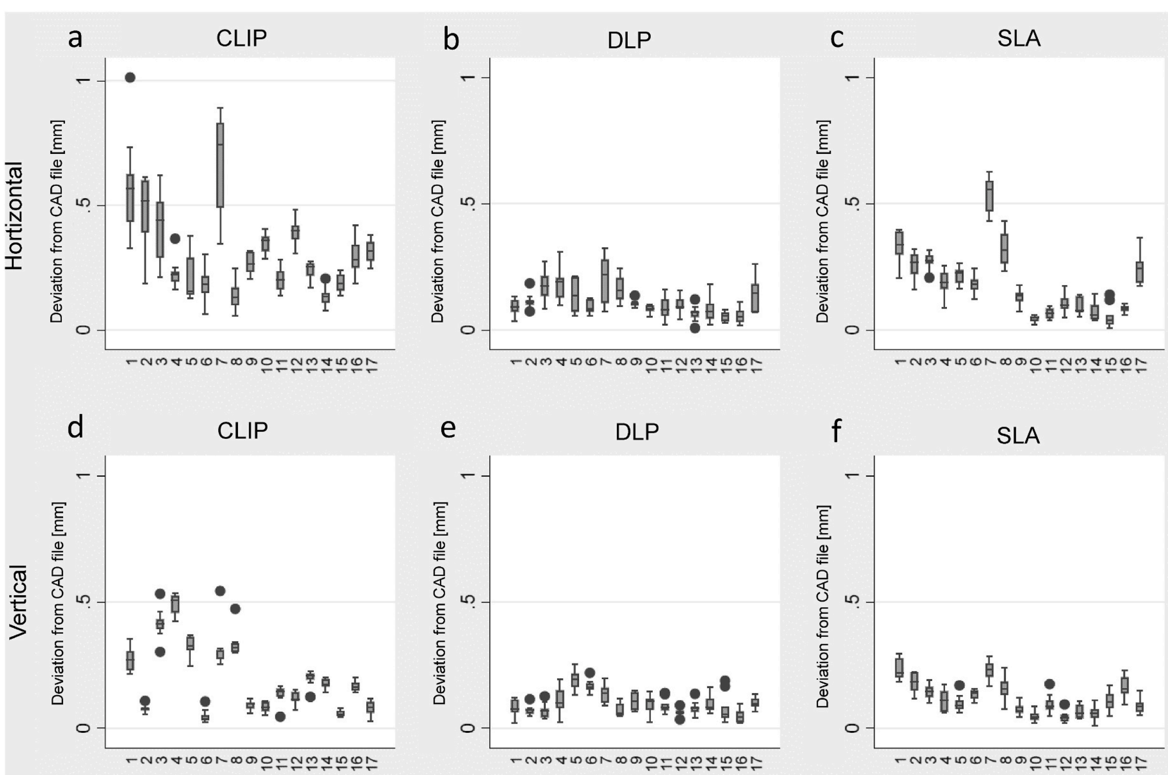

Fig. 7. Boxplot visualizing the vector length indicating the deviation of the 17 reference points after steam sterilization for the groups CLIP (a, d); DLP (b, e); and SLA (c, f). The upper row represents the horizontally printed surgical guides, the lower row the vertically printed surgical guides.

printing orientation ($p = 0.12$). Distance e was measured diagonally from reference point 4 to the lower reference point 17. This distance was significantly increased compared to the CAD file after horizontal and vertical AM for all evaluated technologies ($p < 0.01$), which further increased after steam sterilization. The longest distance e was measured in vertical orientation for the CLIP group.

4. Discussion

The aim of this study was to investigate the dimensional accuracy of surgical guides manufactured in different AM processes and their behavior after steam sterilization, since trueness and precision of surgical guides has a relevant impact on predictable implant positioning (Hüfner et al., 2023). To the best of our knowledge, this is the first study to investigate the dimensional accuracy and sterilization ability of surgical guides manufactured using the novel CLIP technique (Tumbleston et al., 2015). Besides a rapid process, this method is often characterized by a smooth and layer-free surface of the printed objects. Therefore, it was also investigated whether the printing orientation has an influence on the printing accuracy as described for common vat

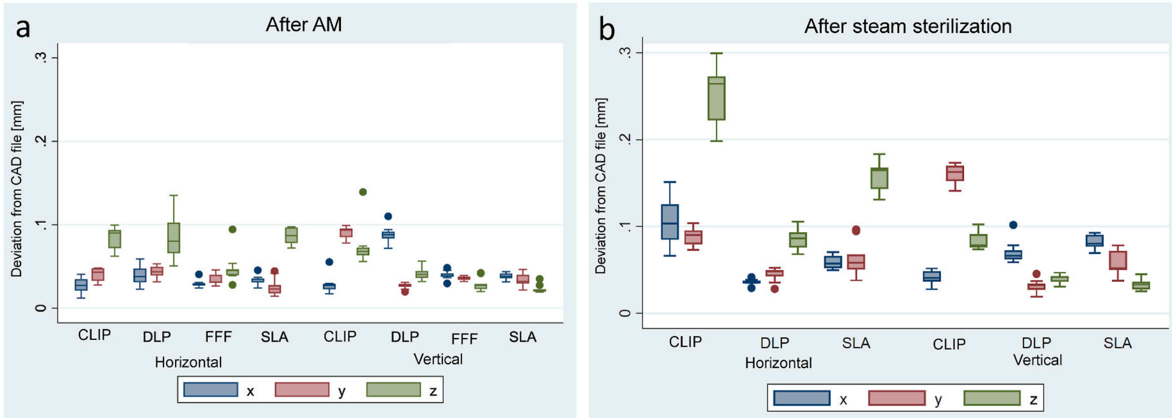

Fig. 8. Deviation of the 17 reference points after AM (a) and after steam sterilization (b) in x-, y-, and z-axis of the scans. *(color artwork)*.

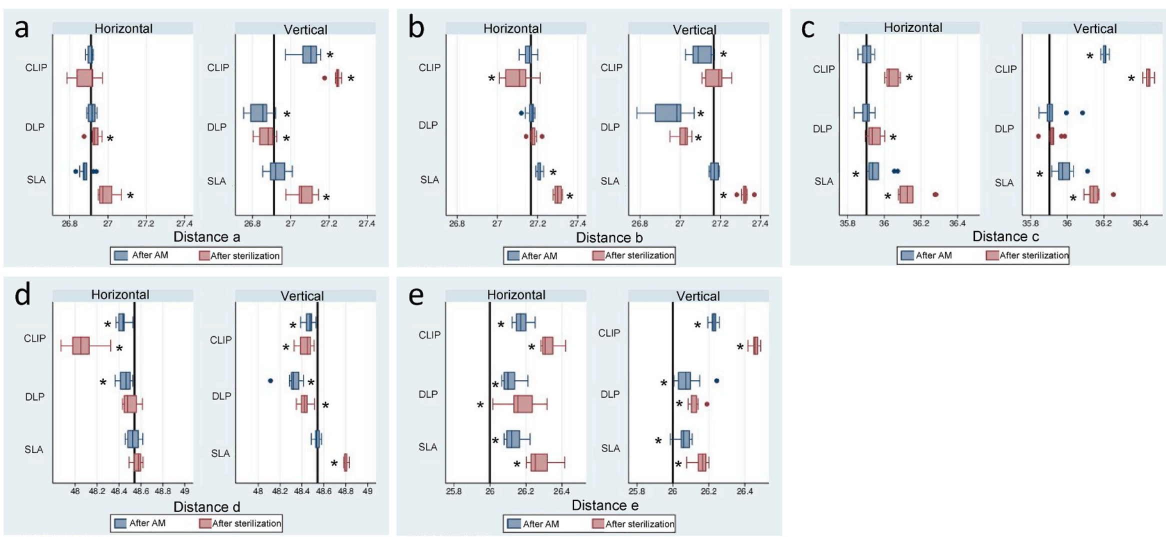

Fig. 9. Boxplots visualizing distance a (a); distance b (b); distance c (c); distance d (d); and distance e (e) for the printing techniques CLIP, DLP, and SLA in horizontal and vertical printing orientation after AM (blue) and after steam sterilization (red). Asterisks (*) indicate statistical significances of the measured distances to the CAD file ($p < 0.05$). *(color artwork)*.

photopolymerization techniques (Diken Turksayar et al., 2022; Nold et al., 2021; Unkovskiy et al., 2018).

The extrusion-based manufactured surgical guides with a PETG filament were as accurate as those manufactured with the other light-curing techniques. Considering the RMS and vectors, no differences were found between the vertical and horizontal printing orientation for the extrusion-based surgical guides. However, the FFF surgical guides made of PETG could not be sterilized dimensionally stable, making them unsuitable for clinical application in a surgical field. This was in accordance with another preclinical study (Garnica-Bohórquez et al., 2023), where significant changes of the mechanical and dimensional properties of surgical guides made of polylactic acid (PLA) were observed after sterilization at 132 °C. This can be explained by the thermoplastic nature and low glass transition temperature of PLA, whereas the glass transition temperature of PETG is only slightly higher (Sava et al., 2023). According to the manufacturer, the market-available filament is also intended for the fabrication of surgical guides; however, there is no recommendation regarding the sterilization of the material. The Centers for Disease Control and Prevention (CDC) of the U.S. National Institutes of Health recommends sterilization of surgical guides in industry-standard steam autoclaves (Rutala and Weber, 2019). For this reason, the demand of autoclavable filaments appears to be high, since this technique represents a comparatively straightforward and cost-effective 3D printing process with only minimal post-processing (Burkhardt et al., 2022; Lüchtenborg et al., 2021). In a comparable pre-clinical study, extrusion-based printed surgical guides were also found to be highly accurate after AM (C. Zhang et al., 2022). A randomized clinical trial compared single-tooth implants placed with FFF surgical guides made of PLA to implants placed with SLA surgical guides (Sun et al., 2022). The results showed that the implants inserted with FFF surgical guides were equally accurate. However, in both studies the surgical guides did not undergo a sterilization procedure, thus no conclusion can be drawn regarding their use according to CDC recommendations. In contrast to the present results, other studies have shown that FFF printed surgical guides were dimensionally stable after steam sterilization (Pieralli et al., 2020; Rothlauf et al., 2023). This can be attributed, for example, to a sterilization temperature of 121 °C and a material composition with more thermostable copolymers (Pieralli et al., 2020; Rothlauf et al., 2023; Yazigi et al., 2023).

No significant differences were observed between all investigated groups after AM and after steam sterilization considering the RMS of the corpus, whereas FFF was excluded for further evaluation after sterilization. For the RMS, the root of the mean of the squares of the differences between the individual measurements and the reference value were calculated. The RMS provides a scalar value but does not convey directional information and does not provide relevant information regarding distances. It treats all deviations from the reference value as positive values when squaring the differences (Majeed-Saidan et al., 2023). As a result, it does not differentiate between over- and underestimations or provide information about the direction of errors. Therefore, in this study, additional reference geometries were integrated to evaluate the direction of the deviation and allow point-to-point measurements (Goodacre et al., 2016). For this approach, it is necessary that the reference geometries do not change significantly or influence the deformation of the sample (Yoon et al., 2018). Due to the advantages and disadvantages of the RMS and the reference geometries, both approaches were evaluated in the present study, which distinguishes this study from investigations that only consider the RMS.

When comparing the light-curing methods CLIP, SLA, and DLP after AM, the deviation of the reference points was similarly pronounced. It was noticeable that each subgroup manufactured in horizontal orientation, showed the strongest deviation in z-axis after AM. Accuracy of AM objects can vary along the different printing axes (x, y, and z), and the z-printing axis occurs often to be less accurate than the x- and y-axes (Hüfner et al., 2023; Unkovskiy et al., 2018; C. Zhang et al., 2022). Possible reasons can be the increased number of layers in z-axis in horizontal printing orientation as well as the typically higher layer height in z-axis than the achievable resolution in x- and y-axis (Stansbury and Idacavage, 2016). The accuracy of printing in z-axis relies on the layers below being sufficiently solid and adhered to the printing platforms. Although the fabrication of medical devices with fine and complex structures using CLIP (Janusziewicz et al., 2020) and their swelling behavior in liquids (Janusziewicz et al., 2022) is described in the literature, there is no data available regarding the behavior after steam sterilization. After steam sterilization, the reference points deviated from the CAD file to varying degrees for the different printing techniques. In particular, increased vectors were calculated in the marginal areas of the surgical guides of the CLIP and SLA groups, which were more pronounced in the CLIP groups. This was in accordance with the heatmaps indicating the highest deviations in the marginal areas of the corpus of the surgical guide. The CLIP surgical guides were manufactured with standard settings including slicing of the CAD file with the height of 0.1 mm. Since some printing technologies showed a larger deformation when printed with smaller layer height (W. Zhang et al., 2022), the higher deformation of the CLIP group could be due to the lower slicing of 0.1 mm compared to the other groups, although the CLIP technology is often referred to as a layer-free technology. However, textures were detected on the surface and it was not completely smooth (Fig. 10). In addition, a significant influence of the printing orientation on the dimensional accuracy of the surgical guides was observed. This was shown, for example, by the significant increase of both lateral distances a and c after vertical AM, whereas horizontal printing showed no significant differences of these distances to the CAD file. Both printing orientations showed a reduced trueness of the reference points in the marginal areas after sterilization, which was additionally accompanied by a reduced precision for the horizontal printing orientation. Based on the present results, it can be concluded that alternative mild sterilization methods for medical devices made by CLIP without heat, such as hydrostatic high-pressure (HHP) sterilization, may be an appropriate alternative (Linares-Alvelais et al., 2018; Valls-Esteve et al., 2023).

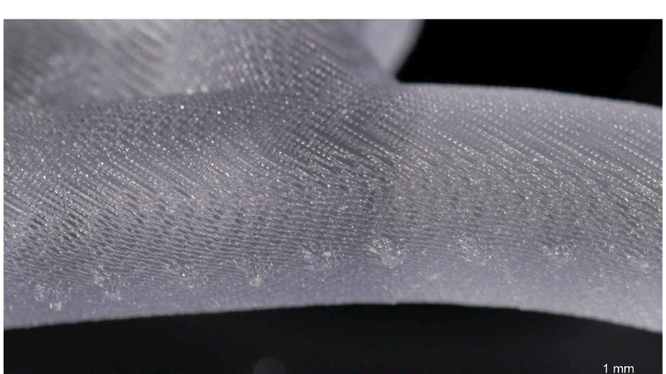

Fig. 10. Detailed view of the surface of a CLIP surgical guide manufactured in vertical printing orientation. *(color artwork)*.

After AM, the accuracy of the surgical guides using DLP was similar to the CLIP and SLA methods, which stands in partial contrast to previous studies evaluating the accuracy of dental models (Rungrojwittayakul et al., 2020) and prototypes (Papaspyridakos et al., 2023). When manufacturing implant-supported prototypes, a lower accuracy of DLP prototypes compared to those made by CLIP and SLA was observed (Papaspyridakos et al., 2023). In general, lower accuracy is expected from DLP compared to SLA, as SLA uses a moving laser spot to cure the photopolymer, while DLP cures one layer at a time using a projector with pixel-resolution (Dikova et al., 2018; Németh et al., 2023). Therefore, SLA is assumed to achieve a more complete polymerization, resulting in higher dimensional stability. The fact that DLP nonetheless shows partially equivalent or better trueness and precision than SLA (Németh et al., 2023) can be attributed to errors occurring in SLA technology due to the slow movement of the mirror for the laser beam (Kim et al., 2018). Due to the described differences between the groups and printing orientations, which were significantly observed in particular after steam sterilization when considering the reference points, the null hypothesis was rejected.

It seems not simple to estimate which deviations are clinically acceptable, since there is no consensus on a standard accuracy tolerance for dental applications (Németh et al., 2023). However, there are several studies investigating the dimensional accuracy of surgical guides using different printing technologies (Juneja et al., 2018; Sharma et al., 2020; Wegmüller et al., 2021). It has been observed that an RMS of 0.2–0.5 seems to be a clinically acceptable range (Kim et al., 2020; Sharma et al., 2020). This value was therefore used as a benchmark for our study. Since the RMS of the photopolymerizing printing processes CLIP, DLP and SLA was below 0.5 after both additive manufacturing and steam sterilization, a clinical application seems possible.

However, a limitation of this study is that solely the accuracy of different printing technologies and orientations was compared without evaluating the impact on the accuracy of the implant position. Therefore, in future studies, the fit of the surgical guides should be evaluated on the model after sterilization (Wegmüller et al., 2021), and the positions of the inserted implants should be compared to the planned implant positions (Gielisch et al., 2023; Rothlauf et al., 2023). Another limitation of the present study is that only one design of a surgical guide was investigated since the design can have an influence on the dimensional accuracy (Rothlauf et al., 2023). Surgical guides with minimal extension, intended for the insertion of single-tooth implants, exhibited higher accuracy than those extended across the entire jaw (Rouzé l'Alzit et al., 2022). Although an extended design was examined in the present study, further designs derived from other implant planning softwares should be investigated in future studies.

5. Conclusions

In conclusion and within the limitations of this study, the different printing technologies and printing orientations showed high accuracy with little differences between the groups. However, during steam sterilization at 134 °C, the FFF surgical guides exhibited significant deformation, making their clinical use impossible. The novel CLIP method enabled rapid manufacturing of the surgical guides; however, the accuracy was lower compared to the commonly used vat photopolymerization techniques SLA and DLP after steam sterilization. However, it remains to be investigated whether these deviations from the CAD file compromise the accuracy of placed implants.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Felix Burkhardt: Writing – original draft, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Leon Handermann:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Severin Rothlauf:** Writing – review & editing, Software, Methodology. **Aiste Gintaute:** Writing – review & editing, Data curation. **Kirstin Vach:** Writing – review & editing, Formal analysis. **Benedikt C. Spies:** Writing – review & editing, Supervision, Resources, Methodology. **Jörg Lüchtenborg:** Writing – review & editing, Validation, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Funded by the Berta-Ottenstein-Programme for Clinician Scientists, Faculty of Medicine, University of Freiburg.

References

Ahmad, S., Hasan, N., Fauziya Gupta, A., Nadaf, A., Ahmad, L., Aqil, Mohd, Kesharwani, P., 2022. Review on 3D printing in dentistry: conventional to personalized dental care. J. Biomater. Sci. 33, 2292–2323. https://doi.org/10.1080/09205063.2022.2099666. Polymer Edition.

Aimar, A., Palermo, A., Innocenti, B., 2019. The Role of 3D printing in medical applications: a state of the art. J. Healthcare Eng. 1–10. https://doi.org/10.1155/2019/5340616, 2019.

Burkhardt, F., Schirmeister, C.G., Wesemann, C., Nutini, M., Pieralli, S., Licht, E.H., Metzger, M., Wenz, F., Mülhaupt, R., Spies, B.C., 2020. Pandemic-driven development of a medical-grade, economic and decentralized applicable polyolefin filament for additive fused filament fabrication. Molecules 25, 5929. https://doi.org/10.3390/molecules25245929.

Burkhardt, F., Schmidt, V.D., Wesemann, C., Schirmeister, C.G., Rothlauf, S., Pieralli, S., Brandenburg, L.S., Kleinvogel, L., Vach, K., Spies, B.C., 2022. Tailoring the composition of biocopolyester blends for dimensionally accurate extrusion-based printing, annealing and steam sterilization. Sci. Rep. 12, 20341 https://doi.org/10.1038/s41598-022-24991-z.

Calignano, F., Manfredi, D., Ambrosio, E.P., Biamino, S., Lombardi, M., Atzeni, E., Salmi, A., Minetola, P., Iuliano, L., Fino, P., 2017. Overview on additive manufacturing technologies. Proc. IEEE 105, 593–612. https://doi.org/10.1109/JPROC.2016.2625098.

Chai, J., Liu, X., Schweyen, R., Setz, J., Pan, S., Liu, J., Zhou, Y., 2020. Accuracy of implant surgical guides fabricated using computer numerical control milling for edentulous jaws: a pilot clinical trial. BMC Oral Health 20, 288. https://doi.org/10.1186/s12903-020-01283-4.

Chan, M.-Y., Huang, L.G., Wu, P.-J., Yeh, C.-H., 2021. Study the design parameters of 3D printing surgical guide deformation quantity by disinfection and sterilization. J. Indust. Product. Eng. 38, 499–507. https://doi.org/10.1080/21681015.2021.1943719.

Crump, S.S., 1992. Apparatus and Method for Creating Three-Dimensional Objects. US5121329A.

Dalal, N., Ammoun, R., Abdulmajeed, A.A., Deeb, G.R., Bencharit, S., 2020. Intaglio surface dimension and guide tube deviations of implant surgical guides influenced by printing layer thickness and angulation setting. J. Prosthodont. 29, 161–165. https://doi.org/10.1111/jopr.13138.

Diken Turksayar, A.A., Donmez, M.B., Olcay, E.O., Demirel, M., Demir, E., 2022. Effect of printing orientation on the fracture strength of additively manufactured 3-unit interim fixed dental prostheses after aging. J. Dent. 124, 104155 https://doi.org/10.1016/j.jdent.2022.104155.

Dikova, T.D., Dzhendov, D.A., Ivanov, D., Bliznakova, K., 2018. Dimensional accuracy and surfaceroughness of polymeric dental bridgesproduced by different 3D printingprocesses. Archives of Mater. Sci. Eng. 2, 65–75. https://doi.org/10.5604/01.3001.0012.8660.

Fretwurst, T., Nelson, K., Tarnow, D.P., Wang, H.-L., Giannobile, W.V., 2018. Is metal particle release associated with peri-implant bone destruction? An emerging concept. J. Dent. Res. 97, 259–265. https://doi.org/10.1177/0022034517740560.

Garnica-Bohórquez, I., Güiza-Argüello, V.R., López-Gualdrón, C.I., 2023. Effect of sterilization on the dimensional and mechanical behavior of polylactic acid pieces produced by fused deposition modeling. Polymers 15, 3317. https://doi.org/10.3390/polym15153317.

Gielisch, M., Heimes, D., Thiem, D.G.E., Boesing, C., Krumpholtz, M., Al-Nawas, B., Kämmerer, P.W., 2023. Steam-sterilized and degradable fused filament fabrication-printed polylactide/polyhydroxyalkanoate surgical guides for dental implants: are they accurate enough for static navigation? Int. J. Bioprint. 9, 655. https://doi.org/10.18063/ijb.v9i2.655.

Goodacre, B.J., Goodacre, C.J., Baba, N.Z., Kattadiyil, M.T., 2016. Comparison of denture base adaptation between CAD-CAM and conventional fabrication techniques. J. Prosthet. Dent 116, 249–256. https://doi.org/10.1016/j.prosdent.2016.02.017.

Hüfner, M., David, S., Brunello, G., Kerberger, R., Rauch, N., Busch, C.V., Drescher, D., Bourauel, C., Becker, K., 2023. Autoclaving-induced dimensional changes of three-dimensional printed surgical guides: an in vitro study. Clinic. Oral Implants Res. clr. 14158 https://doi.org/10.1111/clr.14158.

Janusziewicz, R., Mecham, S.J., Olson, K.R., Benhabbour, S.R., 2020. Design and characterization of a novel series of geometrically complex intravaginal rings with digital light synthesis. Adv. Mater. Technol. 5, 2000261 https://doi.org/10.1002/admt.202000261.

Janusziewicz, R., Shrivastava, R., Dahl, D.K., Young, I.C., Bis, M., Whitesell, A.N., Benhabbour, S.R., 2022. Fundamental investigation of sustained and controlled therapeutics release from 3D printed medical devices. Mater. Today Chem. 24, 100978 https://doi.org/10.1016/j.mtchem.2022.100978.

Janusziewicz, R., Tumbleston, J.R., Quintanilla, A.L., Mecham, S.J., DeSimone, J.M., 2016. Layerless fabrication with continuous liquid interface production. Proc. Natl. Acad. Sci. U.S.A. 113, 11703–11708. https://doi.org/10.1073/pnas.1605271113.

Johnson, A.R., Caudill, C.L., Tumbleston, J.R., Bloomquist, C.J., Moga, K.A., Ermoshkin, A., Shirvanyants, D., Mecham, S.J., Luft, J.C., DeSimone, J.M., 2016. Single-step fabrication of computationally designed microneedles by continuous liquid interface production. PLoS One 11, e0162518. https://doi.org/10.1371/journal.pone.0162518.

Juneja, M., Thakur, N., Kumar, D., Gupta, A., Bajwa, B., Jindal, P., 2018. Accuracy in dental surgical guide fabrication using different 3-D printing techniques. Addit. Manuf. 22, 243–255. https://doi.org/10.1016/j.addma.2018.05.012.

Keßler, A., Dosch, M., Reymus, M., Folwaczny, M., 2022. Influence of 3D-printing method, resin material, and sterilization on the accuracy of virtually designed surgical implant guides. J. Prosthet. Dent 128, 196–204. https://doi.org/10.1016/j.prosdent.2020.08.038.

Kim, S.-Y., Shin, Y.-S., Jung, H.-D., Hwang, C.-J., Baik, H.-S., Cha, J.-Y., 2018. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am. J. Orthod. Dentofacial Orthop. 153, 144–153. https://doi.org/10.1016/j.ajodo.2017.05.025.

Kim, T., Lee, S., Kim, G.B., Hong, D., Kwon, J., Park, J.-W., Kim, N., 2020. Accuracy of a simplified 3D-printed implant surgical guide. J. Prosthet. Dent 124, 195–201.e2. https://doi.org/10.1016/j.prosdent.2019.06.006.

Ligon, S.C., Liska, R., Stampfl, J., Gurr, M., Mülhaupt, R., 2017. Polymers for 3D printing and customized additive manufacturing. Chem. Rev. 117, 10212–10290. https://doi.org/10.1021/acs.chemrev.7b00074.

Linares-Alvelais, J., Figueroa-Cavazos, J., Chuck-Hernandez, C., Siller, H., Rodríguez, C., Martínez-López, J., 2018. Hydrostatic high-pressure post-processing of specimens fabricated by DLP, SLA, and FDM: an alternative for the sterilization of polymer-based biomedical devices. Materials 11, 2540. https://doi.org/10.3390/ma11122540.

Lo Russo, L., Guida, L., Mariani, P., Ronsivalle, V., Gallo, C., Cicciù, M., Laino, L., 2023. Effect of fabrication technology on the accuracy of surgical guides for dental-implant surgery. Bioengineering 10, 875. https://doi.org/10.3390/bioengineering10070875.

Lüchtenborg, J., Burkhardt, F., Nold, J., Rothlauf, S., Wesemann, C., Pieralli, S., Wemken, G., Witkowski, S., Spies, B.C., 2021. Implementation of fused filament fabrication in dentistry. Appl. Sci. 11, 6444. https://doi.org/10.3390/app11146444.

Majeed-Saidan, A., Dutra, V., Levon, J.A., Chu, T.G., Morton, D., Alfaraj, A., Lin, W., 2023. The trueness of scans using one intraoral scanner in different partially edentulous conditions. J. Prosthodont. 32, 588–593. https://doi.org/10.1111/jopr.13592.

Németh, A., Vitai, V., Czumbel, M.L., Szabó, B., Varga, G., Kerémi, B., Hegyi, P., Hermann, P., Borbély, J., 2023. Clear guidance to select the most accurate technologies for 3D printing dental models – a network meta-analysis. J. Dent. 134, 104532 https://doi.org/10.1016/j.jdent.2023.104532.

Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D., 2018. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos. B Eng. 143, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012.

Nold, J., Wesemann, C., Rieg, L., Binder, L., Witkowski, S., Spies, B.C., Kohal, R.J., 2021. Does printing orientation matter? In-vitro fracture strength of temporary fixed dental prostheses after a 1-year simulation in the artificial mouth. Materials 14, 259. https://doi.org/10.3390/ma14020259.

Papaspyridakos, P., AlFulaij, F., Bokhary, A., Sallustio, A., Chochlidakis, K., 2023. Complete digital workflow for prosthesis prototype fabrication with double digital scanning: accuracy of fit assessment. J. Prosthodont. 32, 49–53. https://doi.org/10.1111/jopr.13492.

Piedra-Cascón, W., Krishnamurthy, V.R., Att, W., Revilla-León, M., 2021. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: a narrative review. J. Dent. 109, 103630 https://doi.org/10.1016/j.jdent.2021.103630.

Pieralli, S., Spies, B.C., Hromadnik, V., Nicic, R., Beuer, F., Wesemann, C., 2020. How accurate is oral implant installation using surgical guides printed from a degradable and steam-sterilized biopolymer? J. Clin. Med. 9, 2322. https://doi.org/10.3390/jcm9082322.

Pop, S.I., Dudescu, M., Mihali, S.G., Păcurar, M., Bratu, D.C., 2022. Effects of disinfection and steam sterilization on the mechanical properties of 3D SLA- and DLP-printed surgical guides for orthodontic implant placement. Polymers 14, 2107. https://doi.org/10.3390/polym14102107.

Pozzi, A., Polizzi, G., Moy, P.K., 2016. Guided surgery with tooth-supported templates for single missing teeth: a critical review. Eur. J. Oral Implant. 9 (Suppl. 1), S135–S153.

Quan, H., Zhang, T., Xu, H., Luo, S., Nie, J., Zhu, X., 2020. Photo-curing 3D printing technique and its challenges. Bioact. Mater. 5, 110–115. https://doi.org/10.1016/j.bioactmat.2019.12.003.

Revilla-León, M., Sadeghpour, M., Özcan, M., 2020. An update on applications of 3D printing technologies used for processing polymers used in implant dentistry. Odontology 108, 331–338. https://doi.org/10.1007/s10266-019-00441-7.

Rothlauf, S., Pieralli, S., Wesemann, C., Burkhardt, F., Vach, K., Kernen, F., Spies, B.C., 2023. Influence of planning software and template design on the accuracy of static computer assisted implant surgery performed using guides fabricated with material extrusion technology: an in vitro study. J. Dent. 132, 104482 https://doi.org/10.1016/j.jdent.2023.104482.

Rouzé l'Alzit, F., Cade, R., Naveau, A., Babilotte, J., Meglioli, M., Catros, S., 2022. Accuracy of commercial 3D printers for the fabrication of surgical guides in dental implantology. J. Dent. 117, 103909 https://doi.org/10.1016/j.jdent.2021.103909.

Rungrojwittayakul, O., Kan, J.Y., Shiozaki, K., Swamidass, R.S., Goodacre, B.J., Goodacre, C.J., Lozada, J.L., 2020. Accuracy of 3D printed models created by two technologies of printers with different designs of model base. J. Prosthodont. 29, 124–128. https://doi.org/10.1111/jopr.13107.

Rutala, W., Weber, D., 2019. Guideline for Disinfection and Sterilization in Healthcare Facilities.

Sava, Ștefan-D., Lohan, N.-M., Pricop, B., Popa, M., Cimpoeșu, N., Comăneci, R.-I., Bujoreanu, L.-G., 2023. On the thermomechanical behavior of 3D-printed specimens of shape memory R-PETG. Polymers 15, 2378. https://doi.org/10.3390/polym15102378.

Schirmeister, C.G., Schächtele, S., Keßler, Y., Hees, T., Köhler, R., Schmitz, K., Licht, E.H., Muelhaupt, R., 2021. Low warpage nanophase-separated polypropylene/olefinic elastomer reactor blend composites with digitally tuned glass fiber orientation by extrusion-based additive manufacturing. ACS Appl. Polym. Mater. 3, 2070–2081. https://doi.org/10.1021/acsapm.1c00119.

Sharma, N., Cao, S., Msallem, B., Kunz, C., Brantner, P., Honigmann, P., Thieringer, F.M., 2020. Effects of steam sterilization on 3D printed biocompatible resin materials for surgical guides—an accuracy assessment sm atudy. J. Clin. Med. 9, 1506. https://doi.org/10.3390/jcm9051506.

Spoerk, M., Sapkota, J., Weingrill, G., Fischinger, T., Arbeiter, F., Holzer, C., 2017. Shrinkage and warpage optimization of expanded-perlite-filled polypropylene composites in extrusion-based additive manufacturing. Macromol. Mater. Eng. 302, 1700143 https://doi.org/10.1002/mame.201700143.

Stansbury, J.W., Idacavage, M.J., 2016. 3D printing with polymers: challenges among expanding options and opportunities. Dent. Mater. 32, 54–64. https://doi.org/10.1016/j.dental.2015.09.018.

Sun, Yao, Ding, Q., Yuan, F., Zhang, L., Sun, Yuchun, Xie, Q., 2022. Accuracy of a chairside, fused deposition modeling three-dimensional-printed, single tooth surgical guide for implant placement: a randomized controlled clinical trial. Clin. Oral Implants Res. 33, 1000–1009. https://doi.org/10.1111/clr.13981.

Taormina, G., Sciancalepore, C., Messori, M., Bondioli, F., 2018. 3D printing processes for photocurable polymeric materials: technologies, materials, and future trends. J. Appl. Biomater. Funct. Mater. 16, 151–160. https://doi.org/10.1177/2280800018764770.

Told, R., Ujfalusi, Z., Pentek, A., Kerenyi, M., Banfai, K., Vizi, A., Szabo, P., Melegh, S., Bovari-Biri, J., Pongracz, J.E., Maroti, P., 2022. A state-of-the-art guide to the sterilization of thermoplastic polymers and resin materials used in the additive manufacturing of medical devices. Mater. Des. 223, 111119 https://doi.org/10.1016/j.matdes.2022.111119.

Tumbleston, J.R., Shirvanyants, D., Ermoshkin, N., Janusziewicz, R., Johnson, A.R., Kelly, D., Chen, K., Pinschmidt, R., Rolland, J.P., Ermoshkin, A., Samulski, E.T., DeSimone, J.M., 2015. Continuous liquid interface production of 3D objects. Science 347, 1349–1352. https://doi.org/10.1126/science.aaa2397.

Unkovskiy, A., Bui, P.H.-B., Schille, C., Geis-Gerstorfer, J., Huettig, F., Spintzyk, S., 2018. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. Dent. Mater. 34, e324–e333. https://doi.org/10.1016/j.dental.2018.09.011.

Valls-Esteve, A., Lustig-Gainza, P., Adell-Gomez, N., Tejo-Otero, A., Englí-Rueda, M., Julian-Alvarez, E., Navarro-Sureda, O., Fenollosa-Artés, F., Rubio-Palau, J., Krauel, L., Munuera, J., 2023. A state-of-the-art guide about the effects of sterilization processes on 3D-printed materials for surgical planning and medical applications: a comparative study. IJB 9, 756. https://doi.org/10.18063/ijb.756.

Wegmüller, L., Halbeisen, F., Sharma, N., Kühl, S., Thieringer, F.M., 2021. Consumer vs. High-end 3D printers for guided implant surgery—an in vitro accuracy assessment study of different 3D printing technologies. JCM 10, 4894. https://doi.org/10.3390/jcm10214894.

Yazigi, C., Chaar, M.S., Busch, R., Kern, M., 2023. The effect of sterilization on the accuracy and fit of 3D-printed surgical guides. Materials 16, 5305. https://doi.org/10.3390/ma16155305.

Yoon, H.-I., Hwang, H.-J., Ohkubo, C., Han, J.-S., Park, E.-J., 2018. Evaluation of the trueness and tissue surface adaptation of CAD-CAM mandibular denture bases manufactured using digital light processing. J. Prosthet. Dent 120, 919–926. https://doi.org/10.1016/j.prosdent.2018.01.027.

Zhang, C., Yuan, Y., Chen, J., 2022. Material extrusion based fabrication of surgical implant template and accuracy analysis. Materials 15, 1738. https://doi.org/10.3390/ma15051738.

Zhang, W., Lin, X., Jiang, J., 2022. Dimensional accuracy of 3D printing navigation templates of chemical-based sterilisation. Sci. Rep. 12, 1253. https://doi.org/10.1038/s41598-022-05412-7.