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TRUENESS AND PRECISION OF 3D PRINTED SURGICAL GUIDES AFTER STEAM STERILIZATION PROTOCOLS

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ABSTRACT

Background: for construction of 3D-printed surgical guides, various materials have been advocated; however, there is less information regarding how these materials are impacted by steam sterilization at varying temperatures, pressures, and durations. The purpose of this study was to demonstrate the effect of three different steam sterilization protocols on the trueness and precision of surgical guides printed utilizing 3D printing technology.

Materials and Methods: Surgical guide was digitally designed based on a dual scan to fabricate a surgical guide for an edentulous maxilla. To facilitate the simulation of the placement of the maxillary first molars and the maxillary lateral incisors, an experimental surgical guide was printed as the manufacturing process involved the production of 39 guides using clear (Formlabs Surgical Guide Resin) in layers of 50μm.

Surgical guides were randomly divided into three groups each of 13 specimens. The steam temperature of first group (S1) was raised to 121 degrees Celsius for 20 minutes, second group (S2) was heated to 121 degrees Celsius for 15 minutes, and third group (S3) was heated to 134 degrees Celsius for 10 minutes. Measurements were taken of the guides both before and after the sterilization process for examination of the dimensional stability: An optical scan was performed on the surfaces of surgical guides using a MEDIT-SCANNER T710 both before and after the sterilization process inorder to reverse the negative form of the impression image that was obtained to create the final digital model. Surface and geometric characteristics of the surgical guides were investigated using Olympus SZX 11 stereomicroscope.

Results: Perimeter Changes: Group S1 showed a significant decrease in perimeter, while Group S3 increased significantly. Group S2 had no significant change. Area Changes: All groups demonstrated significant changes in the area post-sterilization. Group S2 showed the least impact protocol. Trueness and Precision: Group S2 showed the best results for both trueness and precision, indicating minimal dimensional distortion.

Conclusion: The steam sterilization protocols significantly affect the dimensional stability of 3D-printed surgical guides. Sterilizing at 121°C for 15 minutes provides an optimal balance between sterilization efficacy and maintaining surgical guide integrity.

KEYWORDS: Trueness, Precision, Steam Sterilization, 3D Printing, Surgical template.

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INTRODUCTION

Implant-supported restorations are becoming more and more popular in modern dentistry. They provide an alternative to traditional restorations and prostheses for addressing the problem of missing teeth. Research has shown that restorations supported by implants have high clinical success and survival rates. [1-6] It is crucial to follow accurate laboratory and clinical protocols to achieve a successful implant placement.

Highly accurate, consistent, and rigid surgical guides can enhance the precision of implant positioning and reduce the likelihood of errors and potential complications during surgery. [1]

Utilizing the most advanced technology, a 3D printer or a CAD/CAM device using resin, a digital representation of the surgical guide in three dimensions is used to create a surgical template. The surgical guide in this case incorporates precisely positioned apertures that are intended for the attachment of metallic sleeve guides that are utilized for mounting implant drills. [7-9]

On an analysis of the 3D printing industry, it revealed that most currently devices on the market that are available to laboratories and dentists as surgical guides, suggest that stereolithography is the most common method of production. The restriction that the limited temperature stability of stereolithographic resins in their polymerized state is a characteristic of these resins because of the glass-transition temperature of resins, which can range anywhere from 85 to 157 degrees Celsius, which is approximately the same as the sterilization temperature. [10,11]

Implant surgery is a surgical procedure that involves the insertion of a surgical guide, which brings the patient's blood, injured soft tissue, and bone into direct contact. Sterilization is crucial for surgical guides, to minimize the likelihood of infection and complications following the procedure. Insufficient sanitization of surgical guides can result in infiltration of microorganisms into the exposed surgical site, negatively impacting the longevity of the implant and the success of the procedure. [12] Dental professionals have employed various sterilization techniques, including steam sterilization, gamma and X-ray irradiation, as well as dry heat and radiation sterilization. [13-15] Steam sterilization is the most frequently used method of sterilization in dental practices because it is cost-effective, easy to use, and has been proven to effectively kill microorganisms. [16] The null hypothesis was that there would be no different on dimensional changes or surface geometric characteristics following sterilization.

MATERIAL AND METHODS

This in vitro study was carried out in the conservative department of the faculty dentistry Alexandria University inorder to quantify the changes that occurred in 39 surgical guides, which were produced using 3D printing technology, after being subjected to sterilization procedures.

The sample size was estimated assuming a 5% alpha error and 80% study power. The mean (SD) dimensional deviation after the normal sterilization cycle (121°C) was estimated to be 0.2735 mm (0.2129) and it was 0.014 mm (0.068) for the flash sterilization (134 °C) [7]. Based on the difference between independent means using the highest SD=0.2129 to ensure enough power, the minimum sample size was calculated to be 12 samples per group, increased to 13 samples to make up for processing errors. Total sample number per group x number of groups= 13 x 3 = 39 samples. The sample size was based on Rosner's method calculated by G*Power 3.1.9.7. [6]

A dual scan for fabrication of surgical guide of an edentulous maxilla, the first CBCT scan for the patient wearing the denture, the second CBCT scan for the denture alone. Alignment markers (using radiopaque composite resin markers) for the denture to appear while doing the CBCT for proper design to patients with missing teeth in upper maxillary and mandibular arches.

This scan data was exported as an STL (standard tessellation language) file. Surgical guides were virtually planned using an open-platform implant planning software (Blue Sky Plan® software V4.7; BlueSky Bio L.L.C., Chicago, IL, U.S.A) An experimental surgical guide was designed to simulate the placement of four axial implants in the regions of the maxillary 1st molars right side using implants with 4.6mm X 6 mm, maxillary 1st 4mm X 7mm and maxillary lateral incisors both with 3.5mm X 13mm. An additional 0.7mm was added to the drill depth to account for the additional length for the tip of the drill.

The digital design was saved as an STL file and produced 39 guides using a Formlabs 3D printer (Formlabs Printing Machine, Formlabs Inc., Somerville, MA, USA) and Formlabs surgical guide resin (Formlabs surgical guide, Formlabs Inc., Somerville, MA, USA). The resin surgical guide's production procedures involve using digital light processing (DLP) to cure ultraviolet-photopolymerizing resin (Formlabs surgical guide, Formlabs Inc., Somerville, MA, USA). The guides were produced using clear biocompatible photo-curable resin Dental SG® (Formlabs Inc., Somerville, MA, USA) with a layer thickness of 50 μm and 100 μm. After printing, then immersed the surgical guides in a 90% isopropyl alcohol bath for 10 minutes. Then immersed them in another bath filled with fresh, unused 90% isopropyl alcohol. Then allowed the surgical guides to naturally evaporate from alcohol at room temperature for an additional 30 minutes. After this, we conducted a thorough examination to verify the cleanliness and dryness of the individual components of the surgical guides. The material then underwent photopolymerization at a wavelength of 385nm after 30 minutes of exposure to blue ultraviolet light. Following the manufacturer's UV treatment guidelines and carried out the curing process at a temperature of 70 °C. was observed. A color transition during the post-curing process, specifically from a translucent yellow color to a translucent orange color. Subsequently, thoroughly inspect the guides for any signs of cracks and promptly discard them if any have been identified. The surgical guides were trimmed for any rough marks after the support material was removed and the surgical guide was smoothed with discs and handpiece.

Grouping of tested surgical guides according to the sterilization protocol: Group S1: steam sterilization at a temperature of 121°C for 20 minutes Group S2: steam sterilization at a temperature of 121 °C for 15 minutes Group S3: steam sterilization at a temperature of 134 °C for 10 minutes. The stereomicroscope (Olympus SZX 11 stereomicroscope, Tokyo, Japan) was used to measure the hole area of each surgical guide from all groups before and after sterilization, each in different 4 places performed measurements where the stereomicroscope got pictures that were then used with Top view software program (Version 3.7, Olympus, located in Tokyo, Japan).

For trueness and precision: Each 3D surgical guide from all groups was digitally scanned by using a MEDIT Scan ST dental scanner (MEDIT-SCANNER T710, Medit, South Korea, software version 1.2.7) which allowed 3D models with an 18-megapixel resolution to be produced. The records were saved in stereolithography (STL) file format. Using MeshLab software (GNU Lice]nse Version 2.0).

Sterilization of each study group according to its protocol using autoclave (CASTELLINI C22 CLASS B DENTAL AUTOCLAVE, ITALY), each surgical guide was thoroughly inspected under stereomicroscope magnification following sterilization for any obvious alterations. The characteristics included surface roughness, color, cracking, and overall deformation. Every modification was noted in a descriptive way. Readings were collected as we got two cross-section points and the area and overall diameter of the drilling holes where each guide had 4 holes with different readings arranged as follows: maxillary 1st molars (posterior left and right) & maxillary laterals (anterior left and right). To observe any critical or minimal changes throughout the guide. Also to check if any color changes can be observed clinically.

For the dimensional stability analysis: The surfaces of surgical guides were optically scanned (MeditScanner T710) after sterilization to inverse the obtained negative form of the impression image to produce the final digital model STL mesh file to be resampled into point-cloud data using Medit Analysis software. Then Analyzing surface scan data (Superimposition) before and after the sterilization the STL mesh file was resampled using Medit Analysis, a software tool for analysis, into point-cloud data. Next, the point clouds for the pre and post-sterilization were aligned using the following protocol: Four common points were manually chosen for each surface to complete the first coarse alignment. Then, outer points were excluded using the software's interactive closest point (ICP) approach to complete the fine alignment. To reduce the root mean square of the distance between the aligned point cloud and the reference point cloud, this method repeatedly conducted a mix of translations and rotations. Following alignment, a random selection of 200,000–400,000 points was used to calculate the mean distance and variation between the two point clouds. The pre-and posttreatment data sets' distances were also utilized to create a color map that allowed for visual comparison and calculation of the variations in the changes that occurred. Every recorded value between -2 and +2 mm from the reference surface was given a continuous color scale. Red markers indicated positive distortions above the reference surface, whereas blue markers indicated negative distortions below it. Green was the designation for zero distortion. (Figure 1)

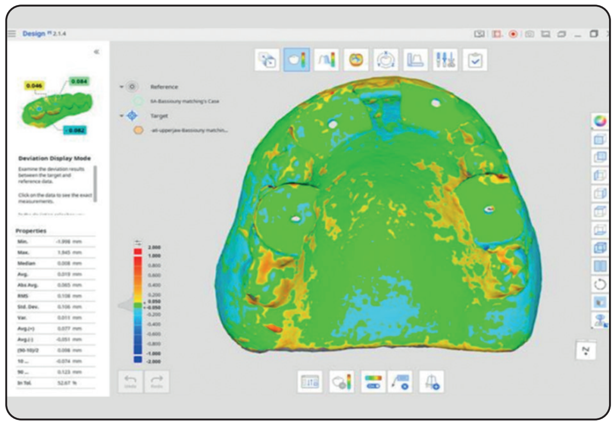

Fig. (1): Shows a color map that allows for visual comparison and calculation of the variations in the changes.

RESULTS AND STATISTICAL ANALYSIS

Data were collected and analyzed using IBM SPSS for Windows version 23, Armonk, NY, USA. Data normality was checked using the Shapiro-Wilk test. The Kruskal Wallis test was used to compare surgical guide perimeter between groups, followed by Dunn's post hoc test with Bonferroni correction. Differences in surgical guide area, deviation, trueness, and precision were analyzed using the One-way ANOVA test followed by Tukey's post hoc analysis with Bonferroni correction. Changes in perimeter and area within each group after autoclaving were analyzed using Wilcoxon Sign Rank and Paired t-tests, respectively. All tests were two-tailed and the significance level was set at p-value ≤0.05.

Upon visual examination, surgical guides showed a complete change in color upon all three groups without any changes in the surface to minor changes in surface structure and texture in the form of superficial cracks of 6 surgical guides (3 surgical guides related to group S3, 2 guides related to group S1 and 1 surgical guide related to group S2) and major changes in 5 guides (3 surgical guides related to group S3, 1 guides related to group S1 and 1 surgical guide related to group S2) in the form of cracks as little, discrete crazing that does not penetrate through the entire thickness, surgical guides demonstrated any cracks or deformations. (Figure 2)

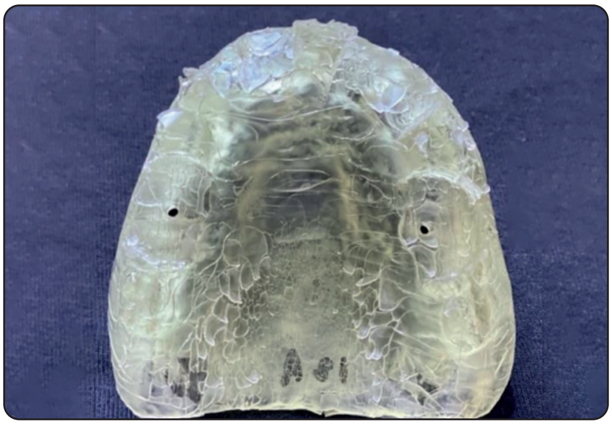

Fig. (2): Showing changes in the surgical guide surface during visual examination.

To further investigate the impact of autoclaving on each group individually, a paired t-test was employed to compare the perimeter before and after sterilization. Group S1, which underwent sterilization at 121°C for 20 minutes, experienced a significant decrease in perimeter (p=0.002). In contrast, Group S3, subjected to a higher temperature of 134°C for a shorter duration of 10 minutes, exhibited a significant increase in perimeter (p=0.001) after autoclaving. Notably, Group S2, sterilized at 121°C for 15 minutes, did not show a significant change in perimeter (p=0.497) after autoclaving. This observation suggests that the intermediate temperature and exposure time used in Group S2 may provide a balance between maintaining the dimensional stability of the surgical guides and achieving adequate sterilization. To compare the magnitude of change in perimeter among the groups, the percent change was calculated and analyzed using the Kruskal-Wallis test.

A highly significant difference (p<0.0001) in percent change was found among the three groups. Group S1 demonstrated the highest reduction in perimeter (-2.4±5.3%), while Group S3 showed the highest increase (1.5±4.8%).

To evaluate the impact of the sterilization protocols on the perimeter change, the percent change was calculated for each group and compared

TABLE (1) :

		Group S1 (n=13)	Group S2 (n=13)	Group S3 (n=13)
Before autoclaving	Mean ±SD	931.2±40.4	916.5±39.2	900.82±43.4
	Median	931.1	917.1	901.9
	Min-Max	816.1-991.9	804.6-989	799.2-996.4
After autoclaving	Mean±SD	907.91±48.1	911.60±40.4	913.5 ±42.5
	Median	915	906.4	916.3
	Min-Max	713.6 – 983.3	803 – 989	811.5 – 994.8
p value#		0.002*	0.497	0.001*
% Change	Mean±SD	-2.4±5.3	-0.5±1.1	1.5±4.8
	Median	-2.1	-0.2	1.1
	Min-Max	-26 – 10.1	-4 – 2.8	-8.1 – 23.3
p value¥			<0.0001*	

Statistically significant difference at p value≤0.05, #Paired t test, ¥Kruskal Wallis test.

pairwise. The results revealed that the percent change in perimeter was significantly different between all group pairs (p<0.0001).

When comparing Group S1and Group S2, the percent change in perimeter was found to be significantly different (p<0.0001). Similarly, a highly significant difference (p<0.0001) in the percent change of perimeter was observed between Group S1 and Group S3.

Lastly, the pairwise comparison between Group S2 and Group S3 also revealed a highly significant difference (p<0.0001) in the percent change of perimeter.

Comparison of change in surgical guide area among the study groups before and after autoclaving: Remarkably, after exposing the surgical guides to their respective sterilization protocols, no significant difference in the area was found among the groups (p=0.794), as indicated by the Kruskal Wallis test. Table 2

To further investigate the impact of autoclaving on each group individually, the Wilcoxon Sign Rank test was employed to compare the area before and after sterilization. All groups demonstrated a significant change in the area after autoclaving (p≤0.026). Group S1, experienced a significant decrease in area (p=0.001). Similarly, Group S2, exhibited a significant decrease in area (p<0.0001) after autoclaving. Group S3, showed a significant increase in area (p=0.026) after autoclaving.

To compare the magnitude of change in area among the groups, the percent change was calculated and analyzed using the Kruskal-Wallis test. A highly significant difference (p<0.0001) in percent change was found among the three groups. Group S1 demonstrated the highest reduction in area (-4.7±10.2%), while Group S3 showed the highest increase (2.1±6.9%).

Color Mapping of every recorded value between -2 and +2 mm from the reference surface was given a

TABLE (2) Comparison of change in surgical guide area among the study groups before and after autoclaving.

		Group S1 (n=13)	Group S2 (n=13)	Group S3 (n=13)
Before autoclaving	Mean ±SD	68677.9±6133	66492.7±5742	64083.8±6392
	Median	68700	66633	64247.8
	Min-Max	50906.6 – 78200.9	51513.4 – 77675.2	49148.1 – 75941
After autoclaving	Mean±SD	65180.4±6999.2.7	65794.9±5929.9	65313.2±6607
	Median	66205.5	64521.7	65560.1
	Min-Max	39932.2 – 76588.2	50977 – 77675.2	49274 – 78734.8
	p value#	0.001*	<0.0001*	0.026*
% Change	Mean±SD	-4.7±10.2	-1.1±2.1	2.1±6.9
	Median	-4.3	-0.4	1.3
	Min-Max	-45.6 – 23.67	-6.5 – 6.1	-12.2 – 20.3
p value¥			<0.0001*	

Statistically significant difference at p value≤0.05, #Wilcoxon Sign Rank, ¥ Kruskal Wallis test

continuous color scale. There was higher distortion in areas with colors that leaned more toward red or blue. To determine the distribution and relative frequency of values, corresponding histograms were produced. The color mapping investigations revealed that when present, the buccal flange area, the crest of the ridge, and the palate where were most deformities occurred. A significant difference in deviation was observed among the groups ($p<0.0001$), with Group S2 showing the highest negative deviation (-0.20 ±0.09) and Group S3 the highest positive deviation (0.07 ±0.03).

When comparing Group S1 and Group S2, a highly significant difference ($p<0.0001$) was observed in the change in deviation, a highly significant difference ($p<0.0001$) was found between Group S2 and Group S3, and no significant difference ($p=0.120$) was observed between Group S1 and Group S3.

For Trueness, Group S2 showed the least Root mean square (RMS) value (0.15 ±0.040.) followed by Group S3 (0.18 ±0.09) and lastly Group S1 showed the highest RMS value (0.46 ±0.10). The One Way ANOVA test revealed a significant difference between Groups. Tukey's test revealed a significant difference between Group S2 and both Group S1 and S3 ($p<0.001$). However, there was no significant difference between Group S1and Group S3.

For Precision, Group S2 also showed the lowest SD value (0.15 ±0.04) followed by Group S3 (0.17 ±0.08) and Group S1(0.42 ±0.08) which showed the highest precision value. The One Way ANOVA test revealed a significant difference between Groups. Tukey's test revealed a significant difference between Group II and both Group S1 and S3 ($p<0.001$). However, there was no significant difference between Group S1 and Group S3.

DISCUSSION

Currently, guided implant placement protocol involves the creation of a surgical guide based on digital planning using specialized software that combines CBCT radiographic data and intraoral 3D scanning information. The surgical guide fits into the patient's mouth and features accurately positioned holes that direct the implant drills to the precise desired location for the implant. [17, 18] 3D printing is frequently employed to fabricate surgical guides specifically designed for dental implant procedures. The Surgical Guide Resin was specifically formulated for compatibility with Formlabs printers and underwent thorough testing to ensure it meets therequirements for sterilization. [19] The dental laboratory-fabricated surgical guides represent a break in the chain of asepsis during dental implant surgery. Aseptic/clean and sterile procedures, which include preoperative oral disinfection.[20, 21]

The null hypothesis of this study was rejected as there were significant differences in the surface characteristics and dimensions of the 3D-printed surgical guide before and after steam sterilization protocols.

The stereomicroscope examination revealed that most surgical guides exhibited no discernible alterations to the surface after sterilization. However, there was evidence of cracking in the guides, which varied in size and pattern. Some cracks were tiny and discrete, not penetrating the entire material thickness, while others formed delicate reticular patterns. Importantly, no surgical guide broke completely during the experiment.

The presence of these cracks indicates that while sterilization process impacts the guides' structural integrity, it does so in a way that does not compromise their overall usability. The localized nature of the cracks, particularly in areas of continuous sections, suggests that these regions may be more susceptible to stress during the sterilization process. The absence of cracks in the drill sections might indicate that these areas are more robust or less affected by the sterilization conditions applied.

Through the implementation of the Kruskal-Wallis test. Group S1: Exhibited the most notable reduction in perimeter (-2.4%) and area. A decrease of 4.7% is observed, indicating a size reduction when exposed to a temperature of 121 °C for 20 minutes. Group S2: Demonstrated the least amount of change, with a reduction in perimeter (-0.5) and a decrease in area (1.1%), indicating that exposing it to a temperature of 121 °C for 15 minutes yields the most desirable dimensional stability.Group S3: Exhibited a 1.5% increase in perimeter and a 2.1% increase in area, suggesting expansion when subjected to a temperature of 134 °C for 10 minutes. The observed outcomes might be attributed to the substantial influence of Steam sterilization on the dimensional stability of 3D-printed surgical guides. The most significant shrinkage occurred with longer exposure to higher temperatures, whereas shorter exposure to higher temperatures led to expansion. The application of a protocol utilizing a temperature of 121 °C for 15 minutes resulted in minimizing changes in dimensions.

Steam sterilization procedures may impact the dimensions of 3D-printed surgical guides. Although sterilization is necessary, it is vital to select settings with caution to minimize distortion.

Steam sterilization provides killing microorganisms This is achieved by subjecting it to a temperature of 121°C for 15 minutes. (The ISO 17665:2024 standard.) Group S2 concluded that subjecting the guides to a temperature of 121 °C for 15 minutes would provide the optimal combination of sterilization efficacy and preservation of dimensional precision. [22]

The research conducted by Labakoum B et al. [23] was found that steam sterilization at temperatures of 121 °C and 134 °C leads to significant deformation. The analysis using a stereomicroscope showed that the deformation was more pronounced at 134 °C compared to sterilization at 121 °C. This finding suggests that the shape of the drill guide templates in the surgical guide is changed during the process of steam sterilization. In addition, Pop et al. [24] demonstrated that thermal sterilization at temperatures of 121 °C and 134 °C altered the mechanical characteristics of surgical guides. Both studies aligned with our results as we found significant changes in surgical guide characteristics and deformation all over the guides with different sterilization temperatures.

In contrast, Török G et al. [25] conducted a comparison between steam sterilization at 121°C for 20 minutes, and steam sterilization at 134°C for 10 minutes. The results of stereomicroscope examinations show that steam sterilization, regardless of the method used, did not cause any significant alterations or distortions in the dimensions of the guides before and after disinfection and sterilization.

Another study by Shuen C. et al. [26] conducted a comparison of various protocols for steam sterilization. The results of stereomicroscope examinations showed that the temperature of 121°C was compared for 30 minutes, followed by 30 minutes of drying, additionally, the temperature of 135°C was compared for 4 minutes, followed by 10 minutes of drying. These comparisons were made using either the dental office or hospital autoclaving methods. The researchers discovered that the variations in distortion among all the groups were not statistically significant. Nevertheless, they documented the occurrence of cracks in 9 out of the 15 guides utilized in the study, although no instances of complete fractures extending from one side to the other were observed. These findings align with the present results, as indicated by the occurrence of crakes in 11 guides out of the 39.

The superimposition results, represented by color mapping, provided a clear visual representation of the distortions occurring due to the sterilization process. The color mapping indicated distortions. The areas showing the most significant distortions were the buccal flange, the crest of the ridge, and the palate that suggest that these regions are more prone to dimensional changes during sterilization.

The findings highlight the importance of considering these distortions when designing and using surgical guides, as they could potentially impact the accuracy of surgical procedures.

As determined by the One Way ANOVA test Group S2 demonstrated the most minimal deviation (-0.20±0.09), whereas Group S3 showed the greatest deviation (0.07±0.03) and Group S1 (0.03 ±0.01). This further supports the notion that the protocol of Group S2 significantly contribute to superior dimensional stability.

For Trueness, Group S2 showed the least RMS value (0.15 ±0.040.) followed by Group S3 (0.18 ±0.09) and lastly Group S1 showed the highest RMS value (0.46 ±0.10).

For Precision, Group S2 also showed the lowest SD value (0.15 ±0.04) followed by Group S3 (0.17 ±0.08) and Group S1 (0.42 ±0.08) which showed the highest precision value.

After undergoing sterilization, the dimensional changes observed in this study suggest that there may be a compromise in the accuracy of 3D-printed surgical guides. While the change may seem insignificant, deviations greater than 10 µm can impede the precise placement of implants, especially in flapless-guided surgery Verhamme et al.[27]

The research conducted by Sharma et al., and Popescu et al.[28, 29] examined the effects of steam sterilization on the dimensional changes of 3D-printed surgical guides. These studies demonstrated that the sizes of 3D-printed surgical guides undergo alterations following the sterilization process. The findings correspond with the current results, which showed statistically significant variations in dimensions among both experimental groups.

Moron et al.[30] found statistically significant differences in trueness and precision between groups which include the occlusal zone and guide hole ($p < 0.05$). The findings were inconsistent with our results that may be due to change in temperature and exposure time: The intermediate temperature and exposure time in Group s2 (121°C for 15 minutes) likely provided an optimal balance between sufficient sterilization and minimal material distortion. This protocol may allow the material to undergo a more controlled thermal expansion and contraction cycle, resulting in fewer dimensional changes. Group S1, which underwent a longer sterilization period (121°C for 20 minutes), may not have allowed enough time for the material to stabilize thermally, leading to contraction.Group S3, subjected to a higher temperature (134°C for 10 minutes), might have experienced excessive thermal stress, causing significant material expansion.

Material Properties: As UV-photopolymerizing resin used in the surgical guides has specific thermal properties that respond differently to varying sterilization protocols. The material's response to heat can result in microstructural changes, which may manifest as cracks or distortions. The resilience of the material to heat-induced stress plays a crucial role in maintaining dimensional stability. Group S2 results suggest that the material performs best under moderate temperature and prolonged exposure.

Thermal Conductivity and Heat Distribution: Uniform heat distribution during the sterilization process is vital for maintaining dimensional stability. Any uneven heating can lead to differential expansion and contraction, causing distortions. Group S2 lower deviations suggest that the sterilization protocol allowed for more uniform heat distribution, reducing the risk of localized thermal stress. The research conducted by Hüfner et al.[31] demonstrated that both the steam autoclaving cycles and the 3D printing process had a noticeable but slight shrinkage effect on most of the guides.

The impact of these modifications on the accuracy of implant placement remains uncertain. These findings align with the current results, as the majority of the surgical guides exhibited significant alterations.

Shaheen et al. [32] conducted a comparison between Steam heat sterilization at a temperature of 134°C and a total cycle duration of 60 minutes (including heating and cooling), and Gas plasma sterilization at a temperature of 55°C with a total cycle duration of 50 minutes. The percentage changes in volumes achieved through steam sterilization were minimal, with an increase of up to 1.5% in volume. Significant disparities were noted when employing heat sterilization. The study's results suggest that subjecting 3D-printed guides to the high pressure and temperature of the autoclaving process can indeed modify the guides' dimensions.

The current study revealed that prolonged exposure to high sterilization temperatures led to a substantial reduction in guide dimensions. An investigation of how polymer materials react to high temperatures can reveal the underlying mechanism responsible for changes in their size. At elevated temperatures, the increased thermal energy induces greater vibrational and translational motion in the polymer molecules, resulting in their increased proximity to one another. Thermal softening refers to a phenomenon where the 3D-printed guides may experience a reduction in their overall dimensions Apresyan et al. [33]

Resins with elevated glass transition temperatures are generally more resistant to thermal-induced size variations during the sterilization process. This is because high-Tg materials have polymer chains that require a higher amount of thermal energy to overcome intermolecular forces and undergo significant changes in their shape. On the other hand, the photopolymer resins commonly utilized in 3D printing generally have glass transition temperatures that are lower than the standard sterilization temperatures of 121°C or 134°C Revilla-León & Ozcan. [34, 35]

Guides that have larger spans and surface areas are more prone to dimensional changes because they contain a greater amount of material. This increased amount of material is more likely to undergo uneven deformation when subjected to the high temperatures and pressures of the sterilization process. [25] Likewise, guides with thinner walls or more complex geometries may be more prone to distortion. The stresses that arise during sterilization can more readily undermine the structural integrity of these characteristics.

In contrast, the study found that higher temperatures, when used for shorter durations, seemed to result in the expansion of the 3D-printed guides. However, during the sterilization process, sudden drops in temperature and changes in pressure can also cause changes in the conformation of polymer chains, leading to larger overall structures following Chen et al. [36]

This finding aligns with prior studies that have emphasized the significance of optimizing sterilization parameters to maintain the dimensional stability of 3D-printed dental components. [37, 38]

Fom a clinical perspective, Youssef et al. [39] agreed with the current results as group S2 showed the most successful sterilization parameter with minimal changes in area, perimeter, trueness, and precision.

CONCLUSIONS AND RECOMMENDATIONS

The outcomes of this study highlighted that: It is important to carefully choose the parameters for sterilization to reduce distortion as much as possible, Steam sterilization at a temperature of 121 °C for 15 minutes appears to offer the optimal balance between effectively eliminating microorganisms and preserving the integrity of the guide. It is crucial for clinicians and researchers to meticulously assess any alterations in dimensions, as these modifications have the potential to impact the suitability, precision, and overall outcome of the surgical intervention.

Furthermore, this study specifically focused on analyzing surgical guides in isolation, without investigating the influence of dimensional alterations on implant osteotomies and positioning. Subsequent research should validate the efficacy of sterilization-induced distortion by assessing the precision and appropriateness of implant positioning through guide fit and fit tests post-implantation. Further research is required to examine patient related outcomes, different designs for surgical guides and different 3d printing resins.

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