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Clinical Implications of Sterilization Methods Applied to 3D–Printed Implant Surgical Guides: An In Vitro Study

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ABSTRACT

Introduction and aims: This in vitro study evaluated how 3 sterilization methods—autoclaving, ethylene oxide (EO) gas, and hydrogen peroxide gas plasma—affect the mechanical, physical, and dimensional properties of 3-dimensional (3D) printed implant surgical guides. These techniques are widely used in dental practice but differ in mechanism and limitations.

Methods: Twenty specimens were fabricated using a digital light processing printer and divided into 4 groups ($n = 5$): non-sterilized control, autoclaving (121 °C, 15 minutes), EO gas (55 °C, 60 minutes), and hydrogen peroxide gas plasma (<57 °C, 18 minutes). Mechanical tests evaluated flexural strength, modulus, and Shore D hardness while translucency and dimensional stability were also assessed. Shape deviation and implant positioning accuracy were compared before and after sterilization. Data were analyzed with one-way analysis of variance and Tukey's post hoc test.

Results: All sterilized groups maintained internal fit deviations within clinically acceptable tolerance (±120 μm), showing no significant differences in overall dimensional accuracy. Implant placement precision was preserved, with implant–tooth distances ≥2 mm. EO sterilization significantly increased the flexural strength (122.49 ± 10.10 MPa) and modulus (3477 ± 161 MPa) compared with controls whereas autoclaving showed the lowest strength (92.40 ± 15.06 MPa). Shore D hardness exceeded 90 HS in all groups, with autoclaving producing the highest values. Only EO treatment significantly reduced translucency.

Conclusion: Sterilization method influenced the mechanical and optical properties of 3D-printed surgical guides without compromising dimensional accuracy.

Clinical relevance: The findings provide evidence-based guidance for clinicians to select sterilization protocols that preserve the functionality of 3D-printed surgical guides and ensure precision in implant placement.

Introduction

Dental implants are widely accepted as a reliable treatment for replacing missing teeth, and the clinical use of implant surgical guides has become increasingly common to enhance procedural accuracy and patient outcomes.[1,2] Implant surgical guides are designed to match the unique dental and oral anatomy of individual patients, reducing the risk of injury to anatomical structures and enabling precise implant

Abbreviations: 3D, 3-dimensional; AC, autoclaving; EO, ethylene oxide; LP, low-temperature hydrogen peroxide gas plasma; DLP, digital light processing; IPA, isopropyl alcohol; STL, standard triangle language; TP, translucency parameter; HS, Shore hardness; ANOVA, analysis of variance; SD, standard deviation

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placement.[3,4] In recent years, advancements in 3-dimensional (3D) printing technology have simplified fabrication, improved cost-effectiveness, and expanded the use of 3D-printed implant surgical guides.

Although implant surgical guides are not inserted into tissue, they are placed intraorally during surgery and directly contact the patient's oral tissues, including the mucosa, teeth, and, in some cases, exposed bone at the implant site;[5-7] thus, they are classified as semicritical medical devices. Notably, they are exposed to biological contaminants, including saliva, blood, and surgical wounds, increasing the risk of cross-contamination and pathogen transmission. Contamination may also occur during fabrication, post processing, storage, and transportation. Therefore, to minimize microbial infection risk and postoperative complications, these guides must undergo disinfection and sterilization before clinical use.[5,6]

Common sterilization methods in dental practice include steam autoclaving (AC), ethylene oxide (EO) gas sterilization, and hydrogen peroxide (H_2O_2) gas plasma sterilization.[8] Steam AC remains widely preferred for its proven effectiveness, accessibility, and cost-efficiency; however, its high temperature and pressure can compromise the dimensional stability and mechanical properties of the thermosensitive resin-based materials often employed in 3D printing.[9] Although low-temperature sterilization methods, such as EO and H_2O_2 gas plasma sterilization, are increasingly applied to thermolabile materials, they also have distinct limitations. For instance, EO sterilization requires lengthy processing and thorough postprocessing aeration to remove residual toxic gases, whereas H_2O_2 gas plasma sterilization is faster but involves expensive equipment and consumables.[10,11] Thus, the appropriate sterilization method should be selected based on the surgical guide's material properties to preserve clinical performance.

Maintaining the accuracy and structural stability of surgical guides following sterilization is essential for successful implant placement as any deformation or bending can cause deviations in implant positioning, resulting in improper insertion angulation, poor prosthesis fit, or even implant failure.[12] Previous studies have reported varying effects of different sterilization techniques on the dimensional accuracy and mechanical properties of dental surgical guides.[13,14] However, findings are often inconsistent, and studies frequently examine only 1 or 2 sterilization methods. Moreover, limited research exists on the impact of sterilization on translucency and how such changes affect clinical applicability and accuracy during implant placement.

Therefore, the present study evaluates the effects of 3 commonly used sterilization methods, namely AC, EO gas sterilization, and H_2O_2 gas plasma sterilization, on the key characteristics of 3D-printed implant surgical guides, including accuracy, clinical applicability, and mechanical (flexural strength, elastic modulus, and Shore hardness) and physical (translucency) properties. The null hypothesis was that there would be no significant differences in the accuracy and mechanical and physical properties of the 3D-printed guides among the different sterilization methods. The findings are expected to help clinicians choose a sterilization protocol that ensures effective infection control while maintaining the guide's essential properties for accurate and predictable implant placement.

Materials and methods

Materials

A commercially available ultraviolet (UV)-curable acrylate-based resin designed for producing customized surgical guides (NextDent SG; 3D Systems) was used in all experiments. The SG resin consisted chemically of ethoxylated bisphenol A (>60% w/w) and methacrylate oligomer (15%-25% w/w), with a small proportion of phosphine oxides (<2.5% w/w) containing UV-sensitive (Blue UV-A, 315-400 nm) initiators for polymerization.

3D printing and sterilization procedure

All specimens, except those employed for the internal-fit test, were designed using a 3D printer software (3D Sprint, 3D Systems) before printing. The completed design was positioned in the 3D Sprint software, and after adding supports, it was converted to a standard triangle language (STL) file. Specimens were fabricated using a digital light processing (DLP) 3D printer (ND 5100; 3D Systems) with a wavelength of 405 nm and a layer thickness of 50 μm. The 3D-printed specimens were post treated as follows: each printed specimen was placed in isopropyl alcohol (IPA) and ultrasonically cleaned for 3 min, supports were removed, and then specimens were placed in fresh IPA and ultrasonically cleaned for 2 minutes. Posttreated specimens were then cured using a light polymerization unit (NextDent LC-3D print box, 3D Systems) with UV light of 350 to 500 nm for 10 minutes. All fabrication processes and experiments were conducted under ambient laboratory conditions (23 $\pm$ 2 °C, 50% $\pm$ 10% relative humidity).

Sterilization of the 3D-printed surgical guides was performed as described in Table 1.

Evaluation of surgical guide internal fit

An experimental model was prepared by creating a full-arch silicone impression of a 3D-printed mandibular model and pouring dental stone into it. In total, 30 stone models were produced, with 10 specimens assigned to each experimental group. The stone model used for the surgical guide design

Table 1 – Specifications of sterilization methods in experimental groups.

Group	Group code	Sterilization technique	Specifications
1	Control	None	None
2	AC	Autoclaving	121 °C for 15 min
3	EO	Ethylene oxide gas	55 °C for 60 min
4	LP	Low-temperature hydrogen peroxide gas plasma	<57 °C for 18 min

AC, autoclaving; EO, ethylene oxide gas sterilization; LP, low-temperature hydrogen peroxide gas plasma sterilization.

was scanned using a light model scanner (Medit T710; Medit). Each scanned STL model was imported into Appliance Designer software (3Shape A/S; 3Shape) to design a surgical guide. All subsequent processes followed the same 3D printing procedure applied in other experiments, except for sterilization. Surgical guides were customized for each stone model.

The fit of each guide was evaluated at the incisal and cusp tips of mandibular teeth by measuring the thickness difference of the silicone layer obtained using the silicone replica method and analyzing it in 3 dimensions. The internal surface of each surgical guide, before sterilization, was filled with a low-viscosity silicone indicator (Fit Checker Advanced GC) and positioned on the stone model. A force of 10 N was applied to the guide's external surface, and the silicone was allowed to set. The guide was carefully removed to ensure that the silicone layer remained on the stone model, which was then scanned using a light model scanner. Then, the silicone layer was removed.

The separated guide was cleaned of any remaining silicone indicator before sterilization. Ten specimens per group underwent random sterilization. The sterilized guide was fitted to the corresponding stone model, using the same silicone replica method, and scanned again.

Scanned data from sterilized guides were designated as measured data whereas scanned data from presterilization fit models were categorized as reference data. Both datasets were compared using 3D inspection software (Geomagic Control X; 3D Systems). To evaluate deviations between groups, teeth were specified as regions, a best-fit alignment was applied, and differences in the silicone layer were measured. Maximum and minimum ranges were set at ±0.5 mm, with tolerance levels set at ±0.12 mm. Average values were calculated for analysis.

Analysis of surgical guide shape deviation before and after scanning and sterilization

A mandibular 3D model with a missing left first molar was created based on the patient's computed tomography data (Mimics 26.0, Materialise Corporation). This 3D model was modified to ensure no personally identifiable patient information was collected or recorded. A surgical guide was designed using Appliance Designer software (3Shape A/S; 3Shape) for seating on the prepared model. All subsequent processes followed the same 3D printing procedure used in other experiments, except sterilization. For each sterilization method, 5 surgical guides were fabricated and sterilized. The sterilized guides were then scanned using a light model scanner (Medit T710; Medit).

To evaluate structural changes in the surgical guide before and after scanning and the positional changes of guide holes before and after sterilization, the initial surgical guide design and the scanned poststerilization guide were superimposed using the glove registration function in 3-matic Research 9.0 software (Materialise Corporation). A part-comparison analysis was conducted to determine the degree of agreement between surgical guides before and after scanning and sterilization.

Positional deviation of virtual implant placement

To evaluate the clinical applicability of each surgical guide before and after sterilization, a virtual implant placement simulation was conducted. A total of 20 surgical guides were used and classified into 4 groups as shown in Table 1, with each group containing 5 surgical guides. All surgical guides were mounted under the same conditions on a 3D mandibular standard model with a missing left first molar. Subsequently, implant fixtures with a diameter of 5.0 mm and a length of 10.0 mm were moved along the path of each surgical guide to be implanted into the mandibular model. The implantation depth and direction were controlled by the guide, minimizing errors due to surgeon intervention. To assess the clinical suitability of implant placement, the distance between the implant fixture and the adjacent teeth on both sides was measured. This distance was defined as the shortest distance between the outer surface of the implant fixture and the outer surface of the adjacent tooth root. Repeated measurements were taken at the same reference point using a distance measurement function.

Flexural strength and modulus

Flexural strength (σ) and modulus (E) were determined according to the ISO 20795-2 International Standard. All specimens ($n = 44$) had average dimensions of 64 × 10 (b) × 3.3 (h) mm. A computer-controlled universal testing machine (Model 5942, Instron) with a 1 kN load cell was used to fracture specimens in 3-point flexure. Each specimen was mounted on 2 supports and loaded until fracture at a crosshead speed of 5 mm/min. The values of σ and E were calculated using Equations 1 and 2:

$$\sigma = \frac{3Fl}{2bh^2}, \tag{1}$$

$$E = \frac{F_1 l^3}{4bh^3 d}, \tag{2}$$

where F is the maximum load on the specimen (N), l is the distance between supports (50 mm), b is the specimen width, h is the specimen height (mm), F_1 is the load at a point in the straight-line portion of the load–displacement curve (N), and d is the deflection at load F_1 (mm).

Shore D hardness

The Shore D hardness of 3D-printed surgical guides was measured using a Shore durometer type D tester (HPSD, Schmidt). A pointed indenter penetrated the specimen surface, and the reading was recorded 5 seconds after loading. Five specimens per group were tested, and the results were reported as the average of 10 measurements per specimen.

Translucency

For translucency testing, the disk-shaped (diameter: 10 mm; height: 1 mm) specimens were polished under water cooling with #1200 grit silicon carbide paper using a polishing machine (Ecomet 30; Buehler Ltd.). For each specimen,

CIELAB coordinates were measured using a spectrophotometer (CM-3500d; Konica Minolta, Sensing Inc.). Ten specimens were tested per group, and 3 random areas were measured and averaged for each specimen. The translucency parameter (TP) was calculated using Equation (3):

$$TP = \left[(L_B^* - L_W^*)^2 + (a_B^* - a_W^*)^2 + (b_B^* - b_W^*)^2\right]^{1/2} \quad (3)$$

Statistical analysis

All statistical analyses were performed using IBS SPSS v25.0 (IBM Corp.). Results were analyzed using one-way analysis of variance followed by Tukey's post hoc test. Statistical significance was set at a 95% confidence level ($p < .05$). This in vitro experimental study does not fall under existing reporting guidelines (e.g., CONSORT, STROBE, PRISMA, ARRIVE); therefore, no checklist is applicable.

In this study, the number of specimens per group was determined by reference to previous studies on 3D-printed dental resins, which typically employ comparable sample sizes to achieve a statistical power of approximately 80% with a significance level of 0.05. This sample size was considered sufficient to detect clinically relevant differences based on effect sizes reported in the literature.

Results

Evaluation of surgical guide internal fit

The internal fit of the surgical guides before and after sterilization was evaluated using the silicone replica technique and 3D deviation analysis (Figure 1). Mean deviations between pre- and poststerilization scans were as follows: EO sterilization (-9.44 ± 20.21 μm), AC (7.44 ± 17.21 μm), and LP sterilization (18.33 ± 37.94 μm). The AC and LP groups exhibited the smallest and largest mean deviations, respectively; however, all groups remained within the clinical tolerance of ± 120 μm. No significant differences were observed among groups ($p > .05$), indicating that sterilization did not affect the fit accuracy of surgical guides.

Poststerilization shape deformation

The visualization of the shape differences between the surgical guides before and after scanning and before and after sterilization is shown in Figure 2. The whole shape of the control and sterilized surgical guides was scanned and overlaid on the initial surgical guide for part comparison analysis. The results showed that the shape of each surgical guide was nearly identical to that of the initial surgical guide. Furthermore, when the sterilized surgical guide was overlaid on the control guide, the positions of the guide holes were similar.

The color-coded superimposed images enabled visual assessment of overall shape correspondence and guide hole positioning, and no apparent discrepancies were observed across the evaluated regions. Accordingly, the visual overlap analysis provided an appropriate means of presenting the observed consistency between the surgical guides.

Virtual implant placement accuracy

Distances between implants placed using the initial surgical guide and the adjacent teeth were 4.72 and 5.00 mm for the left second premolar and left second molar (Figure 3). Average distances to the left second premolar were 4.82, 4.67, 4.73, and 4.67 mm in the control, AC, EO sterilization, and LP sterilization groups, respectively. Average distances to the left second molar were 4.94, 5.11, 5.03, and 5.07 mm in the control, AC, EO sterilization, and LP sterilization groups, respectively. All implants placed using the surgical guides met the clinical

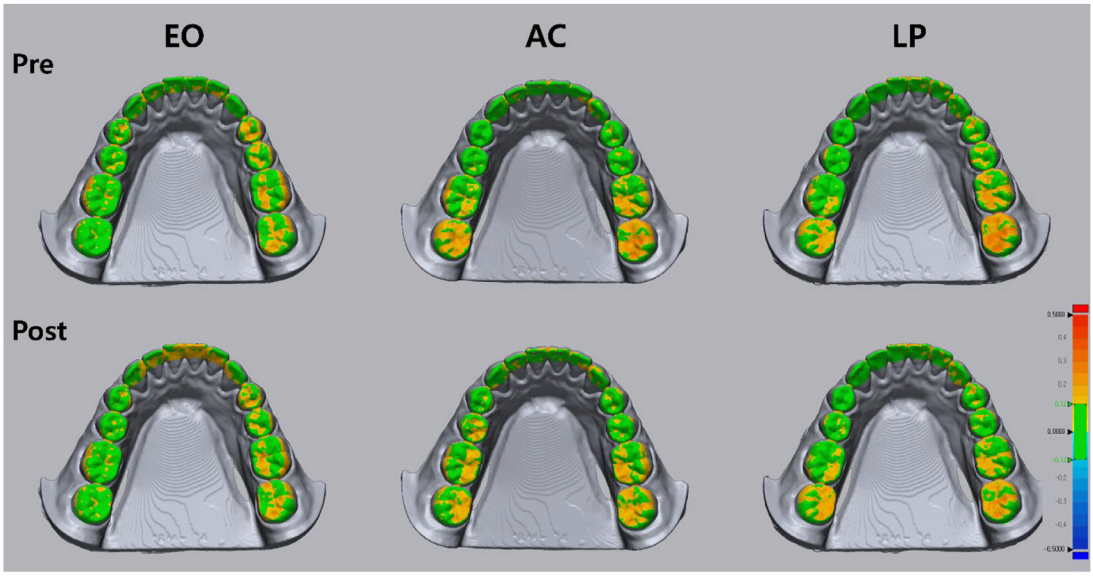

Fig. 1 – Internal fit accuracy of 3D-printed surgical guides before and after sterilization, as shown via 3D superimposition. Green represents a good fit, yellow or red represents a positive error, and blue represents a negative error. EO, ethylene oxide gas sterilization; AC, autoclaving; LP, low-temperature hydrogen peroxide gas plasma sterilization.

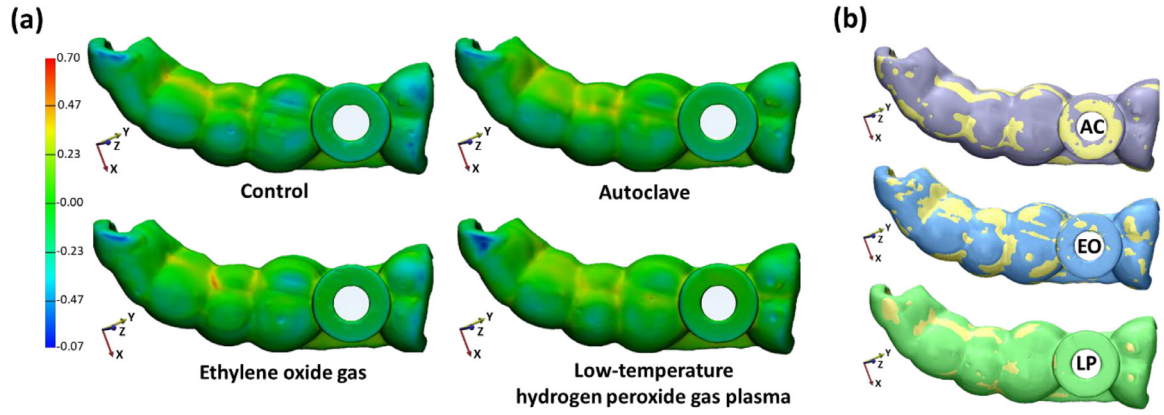

Fig. 2 – (A) Partial comparison of initial and sterilized surgical guides (including a nonsterilized control). In the color map, green indicates a good fit, yellow and red indicate positive error, and blue indicates negative error. (B) Comparison of hole positions between the control and sterilized surgical guides. Control: yellow; autoclaving (AC): purple; ethylene oxide gas sterilization (EO): blue; low-temperature hydrogen peroxide gas plasma sterilization (LP): green.

requirement of a minimum horizontal distance of 2 mm from adjacent teeth.[15]

Flexural strength and modulus

Flexural strength (Figure 4A) was highest in the EO sterilization group (122.49 ± 10.10 MPa), differing significantly from the other groups ($p < .05$), and lowest in the AC group (92.40 ± 15.06 MPa), which differed significantly from the control (106.71 ± 4.91 MPa) and EO sterilization groups ($p < .05$). The control and LP sterilization (105.84 ± 10.78 MPa) groups showed similar flexural strength that did not differ significantly ($p > .05$).

Elastic modulus (Figure 4B) values were 3281 ± 158, 3447 ± 163, 3477 ± 161, and 3476 ± 116 MPa in the control, AC, EO sterilization, and LP sterilization groups, respectively. Elastic modulus was highest under EO sterilization, significantly higher than that in the control group ($p < .05$). Elastic modulus was lowest in the control whereas the AC and LP sterilization groups exhibited intermediate values that did not differ significantly from control or EO sterilization group values ($p > .05$).

Shore D hardness

Shore D hardness values (Figure 4C) exceeded 90 HS in all groups except the control. Shore D hardness in the AC group (91.24 ± 0.60 HS) was significantly higher than that in the control (89.24 ± 0.63 HS; $p < .05$) but did not differ significantly from that in the EO sterilization (90.70 ± 1.07 HS) and LP sterilization (90.76 ± 1.03 HS) groups ($p > .05$)

Translucency

Translucency (Figure 5) was highest in the control (37.13% ± 5.45%) and comparable in the AC (34.10% ± 5.57%) and LP sterilization (34.94% ± 4.07%) groups, with no significant differences observed ($p > .05$). In contrast, the EO sterilization group (30.42% ± 2.44%) showed significantly lower translucency compared with the control ($p < .05$).

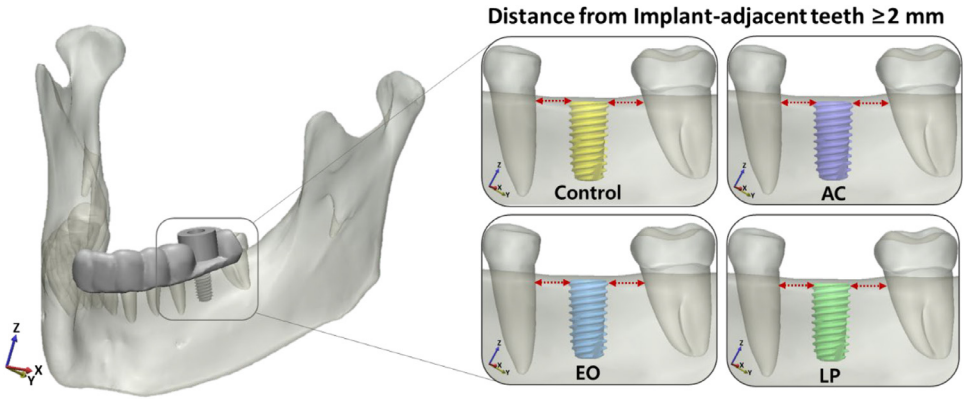

Fig. 3 – Virtual implant placement and distance to the left second premolar and left second molar. Control: yellow; autoclaving (AC): purple; ethylene oxide gas sterilization (EO): blue; low-temperature hydrogen peroxide gas plasma sterilization (LP): green.

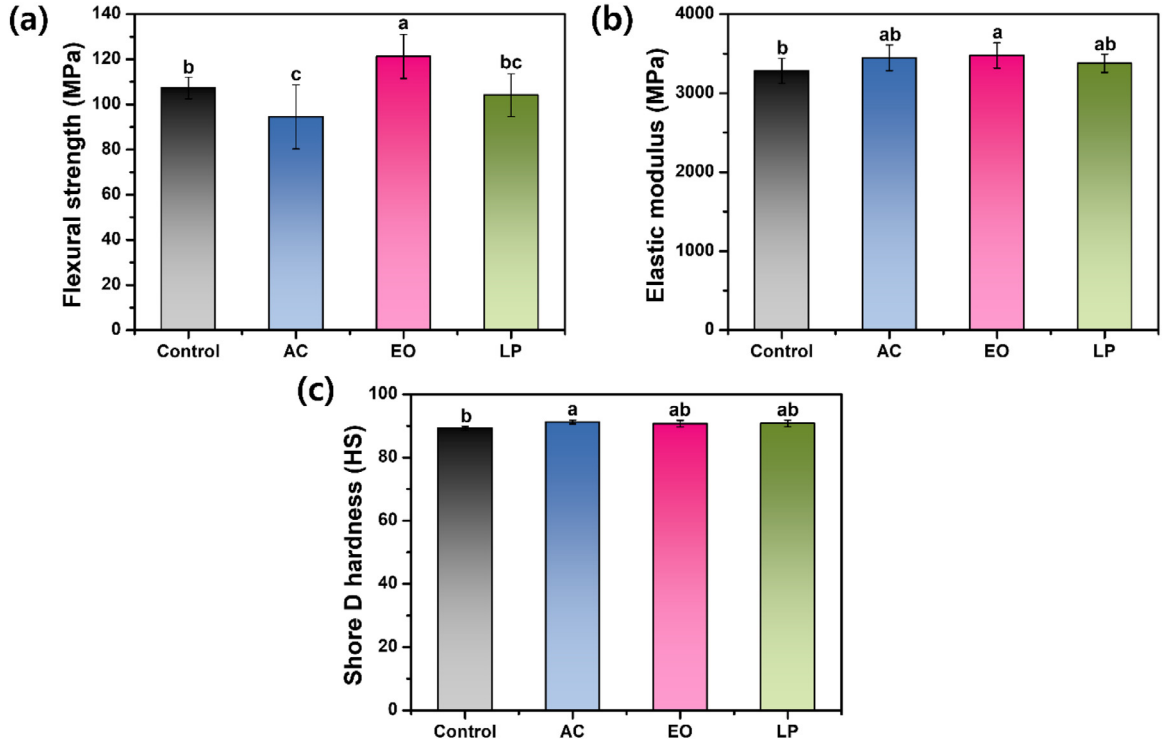

Fig. 4 – (A) Flexural strength, (B) elastic modulus, and (C) Shore D hardness of the specimens after sterilization. Control: unsterilized; AC: autoclaving; EO: ethylene oxide gas sterilization; LP: low-temperature hydrogen peroxide gas plasma sterilization. Error bars represent standard deviations. Different lowercase letters indicate statistically significant differences between groups ($p < .05$).

Discussion

This study evaluated the impact of 3 sterilization methods, AC, EO sterilization, and LP sterilization, on the dimensional accuracy, mechanical properties, and optical characteristics of 3D-printed surgical guides. Although all methods maintained dimensional deviations within clinically acceptable limits (±120 μm), they produced distinct effects on mechanical strength, surface hardness, and translucency. The combined influence of mechanical, physical, and dimensional stability may affect the final accuracy of dental implant placement, making these differences important for mechanical reliability and clinical precision in implant placement.[16,17]

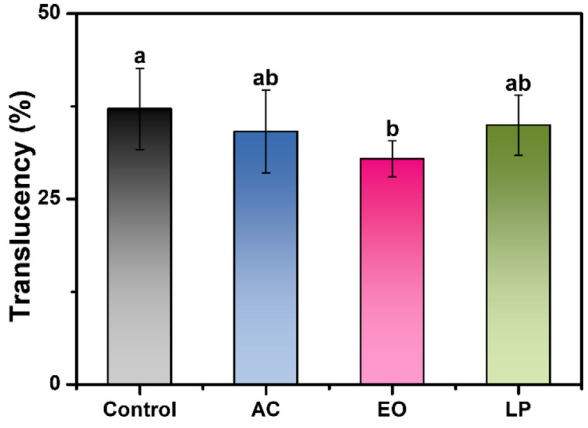

Fig. 5 – Translucency of 3D-printed surgical guides after sterilization. Control: unsterilized; AC: autoclaving; EO: ethylene oxide gas sterilization; LP: low-temperature hydrogen peroxide gas plasma sterilization. Error bars represent standard deviations. Different lowercase letters indicate statistically significant differences between groups ($p < .05$).

Although some groups had positive mean deviation values (AC and LP sterilization) while others showed negative values, these directions reflect deviation direction rather than clinical relevance. Thus, the absolute magnitude of deviation is a better measure of fit accuracy. Among the sterilized groups, AC showed the smallest deviation in internal fit, indicating superior dimensional stability, whereas LP sterilization exhibited the largest variation although still within acceptable limits. These findings align with previous studies reporting minimal deformation after thermal or plasma-based sterilization.[17-19] The observed differences may be attributed to material resistance to short-term heat under AC whereas LP sterilization (a dry, low-temperature process) primarily affects the surface and preserves as-printed microdeviations, particularly in thin features.[20-22] Similar findings by Hüfner et al. demonstrated that AC caused only minor dimensional changes in 3D-printed surgical guides.[9,13]

The mechanical strength of the surgical guide is directly related to its ability to withstand the lateral forces and vibrations generated during the drilling process.[23] A significant reduction in flexural strength could lead to microcracks or

even fracture of the guide during implant surgery, posing a risk of surgical complications.[24] Mechanical testing revealed that EO sterilization significantly enhanced flexural strength and elastic modulus relative to the control and other sterilized groups. This finding is unexpected as sterilization often degrades polymeric materials. The improvement in the EO sterilization group may result from additional polymer cross-linking triggered by gas exposure as suggested by prior studies on low-temperature sterilization of resin-based devices.[10] In contrast, AC significantly reduced flexural strength, likely due to polymer degradation under high heat and pressure. Increased stiffness in EO-sterilized guides may improve rigidity and control during drilling, but excessive stiffness can reduce adaptability to anatomical variations, potentially compromising passive fit. Elastic modulus results followed a similar pattern, with the EO sterilization group exhibiting the highest values and the AC and LP sterilization groups showing intermediate values without significant differences from the EO sterilization or control groups.

Hardness is a crucial factor in evaluating surface wear resistance and selecting suitable drilling tools for surgical procedures.[25] All sterilization methods led to increased Shore D hardness compared with the control, with AC producing the highest values. This suggests that sterilization causes surface hardening, potentially improving resistance to deformation during clinical use. These results are consistent with previous reports documenting increased surface rigidity after sterilization of 3D-printed resins.[26,27] Furthermore, the maintenance of surface integrity is essential for the clinical reliability of 3D-printed components. As highlighted by Saadi et al., 3D-printed dental materials can exhibit different wear resistance and surface stability depending on their processing and environmental exposure.[28] Although surgical guides are intended for single-use, preserving appropriate surface hardness—as emphasized in the wear analysis of other 3D-printed dental applications—is critical to prevent resin debris shedding and to ensure smooth instrument guidance during the drilling process.

Regarding optical properties, EO sterilization significantly reduced translucency, which may hinder visual verification of guide seating during implant placement.[29,30] This aligns with prior findings showing optical changes in resin materials following sterilization under gas exposure.[31] Conversely, the AC and LP sterilization group translucency values were comparable to the control, suggesting that these methods may be preferable when visual access during surgery is important.[32]

The minimum measured distance between an implant and adjacent tooth was 4.53 mm (LP sterilization group), exceeding the recommended minimums: 2 mm from a natural tooth and 3 mm from another implant. This confirms that guides, even after sterilization, maintain high positional accuracy and adequate clearance from adjacent structures, which is especially important in anatomically restricted cases. The findings indicate that 3D-printed surgical guides sterilized using these methods can be safely and reliably used in narrow interproximal spaces without risking proximity to critical structures. In addition to these findings, the 3D model –based virtual implant placement method proposed in this study differs from prior work by Mengxi Yang et al., by enabling a multidimensional evaluation of implant placement outcomes without the need for clinical surgery or in vivo experiments.[33] Furthermore, this approach enables quantitative assessment of the relationship between the implant and surrounding bone structures, providing an efficient and reproducible method for validating various placement scenarios before clinical application.

The observed improvement in mechanical properties (flexural strength, elastic modulus, and hardness) with some sterilization methods suggests that postprocessing could serve to sterilize and enhance 3D-printed surgical guide performance. Indeed, this finding could be utilized in developing optimized postprocessing protocols for improved guide performance. However, trade-offs between enhanced mechanical properties and potential reductions in translucency and dimensional accuracy must be carefully considered. Overall, the choice of sterilization method can substantially affect the mechanical, optical, and structural properties of 3D-printed surgical guides. EO sterilization may be beneficial when increased mechanical strength is desired despite reduced translucency.[34] AC produced the smallest internal fit deviation and highest surface hardness but reduced flexural strength. LP sterilization led to the largest fit variability although it remained within ± 120 μm.[35] Clinicians should balance these trade-offs according to anatomical site, visibility needs, and surgical complexity.[34]

Several limitations of this study should be recognized. First, as an in vitro experiment, the findings require further in vivo validation to fully confirm their clinical relevance. Second, the use of a single resin type and a single sterilization cycle limits the generalizability of these results to other 3D-printing materials or scenarios involving repeated clinical use. Finally, as implant placement accuracy was assessed through virtual superimposition, future research should focus on clinical validation and the impact of multiple sterilization cycles to provide more comprehensive and standardized guidelines for 3D-printed surgical guide preparation.

Conclusion

This in vitro study demonstrated that sterilization methods significantly affect the mechanical, physical, and dimensional properties of 3D-printed implant surgical guides without compromising their clinical applicability, even in anatomically restricted areas. Based on the results, ethylene oxide (EO) sterilization is recommended for 3D-printed surgical guides as it exhibited superior mechanical properties and minimal deviation in virtual implant placement accuracy. Despite these advantages, it is important to note that EO sterilization may reduce translucency, which could hinder visual verification during surgery. To address this, incorporating inspection windows into the guide design is suggested to maintain surgical accuracy and allow for visual confirmation during seating. Future research should evaluate the effects of repeated sterilization cycles and conduct long-term clinical validation to establish standardized protocols for 3D-printed surgical guides in implant dentistry.

Author contributions

H.-B.G.: conceptualization, methodology, investigation, and writing the original draft; G.-T.K., J.-H.Y.: data curation, validation, software, and formal analysis; Y.-J.Y.: resources, validation, and editing the paper; J.-S.K.: supervision, project administration, and reviewing the paper. All authors commented on the paper and approved this manuscript.

Data availability statement

The data will be made available by the corresponding author upon reasonable request.

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Conflict of interest

None disclosed.

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