Wear Resistance of Additively Manufactured Resin with Different Printing Parameters and Postpolymerization Conditions

Qiucen Wan, DDS, MSD
Jae-Hyun Lee, DMD, MSD, PhD, MAS
Department of Prosthodontics and Dental Research Institute, Seoul National University School of Dentistry, Seoul, Republic of Korea.

René Daher, DDS, Dr med dent, PhD
Division of Cariology and Endodontology, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.

Duygu Karasan, DDS, PhD
Division of Fixed Prosthodontics and Biomaterials, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.

Gerelmaa Myagmar, DDS, MSD, PhD
Department of Prosthodontics and Dental Research Institute, Seoul National University School of Dentistry, Seoul, Republic of Korea.

Irena Sailer, Prof Dr med dent
Division of Fixed Prosthodontics and Biomaterials, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.

Purpose: To evaluate the wear resistance of a printed interim resin manufactured with different printing and postpolymerization parameters. ***Materials and Methods:*** Overall, 130 rectangular resin specimens (15 × 10 × 10 mm) were 3D-printed. Among the specimens, 60 were printed with different printing orientations (0, 45, and 90 degrees) and layer thicknesses (50 and 100 μm) to create six groups to investigate the effects of the printing parameters (n = 10 per group). The remaining 70 specimens were used to evaluate the effects of postpolymerization; for this, seven groups were created as follows (n = 10 per group): non-postpolymerized; postpolymerized for 5, 15, and 30 minutes with an ultraviolet light–emitting diode (LED) device; and postpolymerized for 5, 15, and 30 minutes with an ultraviolet light bulb device. After masticatory simulation, the wear volume loss was calculated with 3D metrology software. One-way and two-way ANOVA were used for intergroup comparisons ($\alpha = .05$). ***Results:*** The group printed with a build angle of 45 degrees showed lower wear volume loss than the 0- and 90-degree groups ($P < .01$). The wear volume loss in the ultraviolet LED group was significantly greater than that in the ultraviolet light bulb group ($P = .04$). No significant difference was observed in the wear volume loss of the printed resin with respect to the layer thickness and polymerization time ($P > .05$). However, the non-postpolymerized group showed significantly greater wear volume loss than the other groups ($P < .001$). ***Conclusions:*** The printed resin showed greater wear resistance when it was printed at a build angle of 45 degrees and postpolymerized with an ultraviolet light bulb device. *Int J Prosthodont 2024;37(suppl):s55–s62. doi: 10.11607/ijp.8538*

With the development of digital dental technologies, dental restorations can be digitally fabricated using either subtractive or additive manufacturing techniques.[1,2] Subtractive manufacturing involves direct milling of a block of the desired material to obtain the final object, which results in material waste.[3] In addition, owing to the different mechanical properties of the material and milling tools, structural defects in milled objects may occur with stress concentration.[4] In contrast, additive manufacturing, also known as 3D printing or rapid prototyping, is economical and helps reduce production costs.[3] The target object is manufactured layer by layer using 3D design data from computer-aided design (CAD) software. Additive manufacturing

Correspondence to:
Prof Dr Jae-Hyun Lee,
jaehyun.lee@snu.ac.kr

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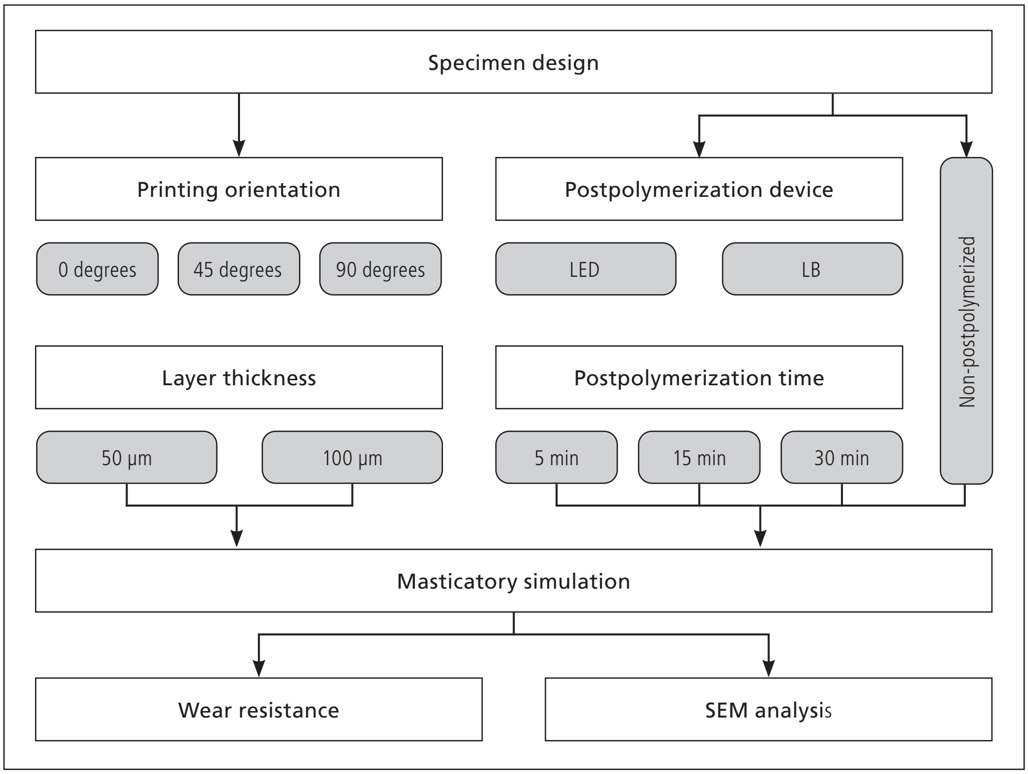

Fig 1 Flowchart of the study process.

is time-efficient, as multiple objects can be fabricated simultaneously. Moreover, it enables the fabrication of complex geometries.[5–9] Based on these advantages of additive manufacturing over subtractive manufacturing, 3D printing has gained popularity in dentistry for manufacturing interim restorations, removable dentures, dental models, surgical guides, and orthodontic aligners.[5,10–12]

Various types of 3D-printing polymer materials have been developed as interim restorative materials. Interim restorations, as a transition between tooth preparation and final restorations, protect the prepared tooth, restore mastication function and esthetics, and stabilize the occlusion.[13,14] Furthermore, when long-span interim restorations are used for extensive oral reconstruction, the material should possess satisfactory optical[15] and mechanical properties, such as high wear resistance and adequate hardness, for long-term use.[16,17] This is because, in long-span restorations, interim restorations are mainly used to evaluate the adequacy of the vertical occlusal dimension or intermaxillary relationship. If the interim restoration is easily worn down, loss of vertical occlusal dimension will occur, and the initially planned vertical dimension cannot be maintained for a sufficient time. This may cause problems in establishing a suitable intermaxillary relationship during definitive restorations.[13]

The mechanical properties of additively manufactured restorations can be affected by both the material type and the manufacturing procedures.[14] Previous studies have reported that controllable printing parameters (such as the printing orientation and layer thickness[18–23]) and postpolymerization procedures may influence the mechanical properties of printed resin materials.[24–26] Flexural strength, hardness, and fracture strength of printed interim resin materials have been investigated in several previous studies,[14,18,23,24,26–34] while studies on their wear resistance are scarce.[17,35] Manufacturing factors (such as printing orientation, layer thickness, and postpolymerization strategies) may also affect the wear resistance of 3D-printed resins. Therefore, the present study aimed to evaluate the influence of printing orientation, layer thickness, postpolymerization device, and postpolymerization time on the wear resistance of 3D-printed resins. The null hypothesis of the present study was that the printing orientation, layer thickness, postpolymerization device, and time would not influence the wear resistance of the printed resins.

MATERIALS AND METHODS

Specimen Preparation

Specimens for evaluating the effect of printing parameters and specimens for evaluating the effect of postpolymerization were fabricated separately in this study (Fig 1). The sample size of the present study was calculated with a significance level of 0.05, power of 80%, and effect size of 0.42 for wear volume loss. The effect size was obtained from previous studies.[17,36] Rectangular specimens

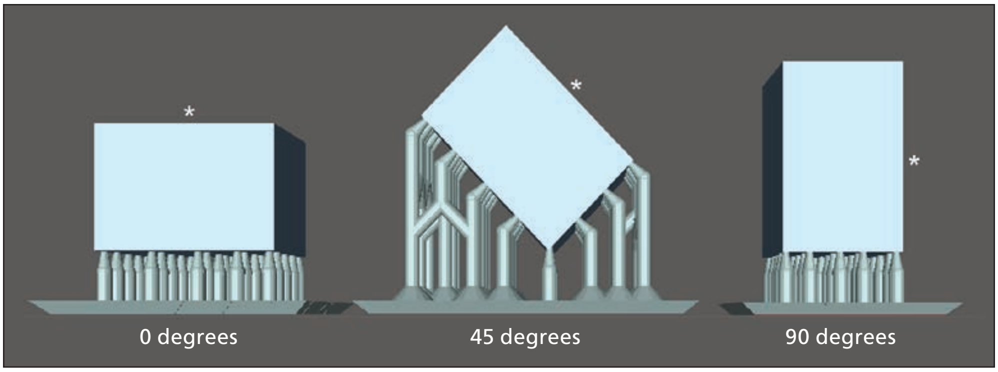

Fig 2 Printing orientation for specimens. Asterisks (*) are placed by the surfaces to be worn.

Table 1 Materials Used

Material	Brand	Composition[a]	Manufacturer	Lot no.
3D-printing resin	C&B MFH, shade N1	Methacrylic oligomers > 60%, glycol methacrylate 15%–25%, phosphine oxides < 2.5%	NextDent	WX151N01
Abrader	Luxen Enamel, shade E2	ZrO_2, HfO_2 > 90%, Y_2O_3 6.95%, other oxides < 0.1%	Dentalmax	BAZF22-25E2P-12

[a] According to the manufacturer's information.

Table 2 Postpolymerization Devices Used in This Study

Brand	Light source	Wavelength[a]	Power output[a]	Manufacturer	Code
CureM U102H	UV LED	395–405 nm	80 W	Graphy	LED
LC-3D Print Box	UV light bulb	300–550 nm	12 × 18-W lamps	NextDent	LB

UV = ultraviolet.
[a] According to the manufacturer's information.

(15 × 10 × 10 mm) were designed using CAD software (Fusion 360, Autodesk) and exported to an STL file.

For the first experiment, the 3D objects were oriented at three different angles (0, 45, and 90 degrees) and the printing layer thicknesses were set to 50 and 100 µm using a slicing software (Composer version 1.2.11, Asiga) to evaluate the wear resistance according to the printing parameters (Fig 2). Thus, six groups were created as follows (n = 10 specimens per group): *(1)* 0 degrees and 50 µm; *(2)* 45 degrees and 50 µm; *(3)* 90 degrees and 50 µm; *(4)* 0 degrees and 100 µm; *(5)* 45 degrees and 100 µm; and *(6)* 90 degrees and 100 µm.

A printed resin (C&B MFH, shade N1, NextDent) was mixed with a stirring device (LC-3D Mixer, NextDent), and the resin specimens were then printed by a digital light processing (DLP) printer (MAX UV, Asiga). Table 1 lists the product details of the materials used. After printing, the resin specimens were rinsed with absolute ethanol (purity ≥ 99.8%) in a washer for 3D-printed objects (Twin Tornado, MediFive) for 10 minutes. All specimens were then postpolymerized with a light polymerization unit (CureM U102H, Graphy) for 5 minutes at level 3 according to the manufacturer's recommendation. Subsequently, the support structures were removed, and the sides were polished using a low-speed rotary instrument (H334, EVE Ernst Vetter) and silicon carbide papers with grit sizes of 600 and 1,200.

For the second experiment, the same CAD design (15 × 10 × 10 mm) was used to fabricate the specimens to evaluate wear resistance according to the postpolymerization condition. A total of 70 specimens were printed at an orientation of 0 degrees and a layer thickness of 100 µm with the same material (C&B MFH, shade N1) using the DLP printer (MAX UV). The printed specimens were then rinsed with absolute ethanol in the washer (Twin Tornado) for 10 minutes. Subsequently, according to the postpolymerization duration and devices, the specimens were divided into seven groups as follows (n = 10):

- Non-postpolymerized
- LED groups: postpolymerized for 5, 15, and 30 minutes with an ultraviolet light-emitting diode (LED) device (CureM U102H, level 3)
- LB groups: postpolymerized for 5, 15, and 30 minutes with an ultraviolet light bulb (LB) device (LC-3DPrint Box, NextDent)

Table 2 lists the product details of the postpolymerization devices used. The specimens were then subjected to the same polishing and finishing processes.

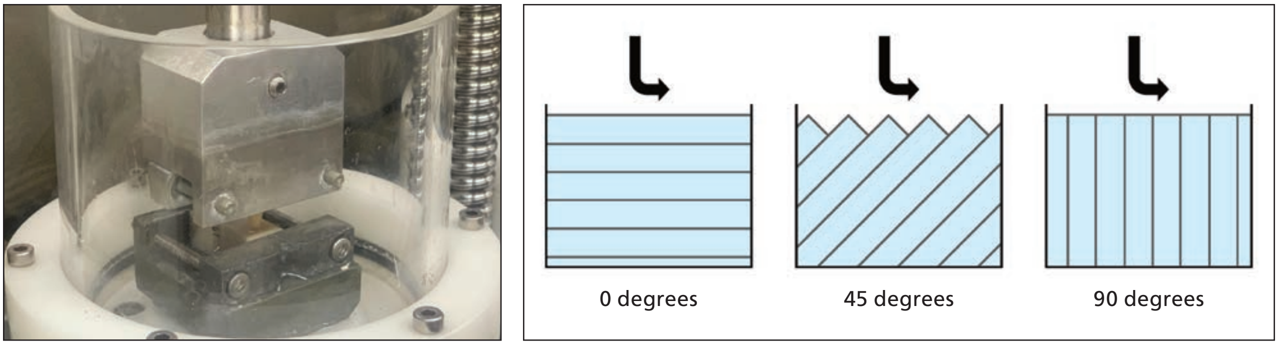

Fig 3 Masticatory simulation. *(a)* Chewing simulator equipped with the specimen and abrader. *(b)* Schematic representation of masticatory simulation for the resin specimens printed with build angles of 0, 45, and 90 degrees. The *arrows* indicate the chewing direction involving a vertical downward movement of 5 mm and a horizontal movement of 2 mm.

Masticatory Simulation

To simulate mastication, an antagonist was designed using CAD software (Inventor, Autodesk). The abrader tip (Luxen Enamel, shade E2, Dentalmax; see Table 1) was shaped as a hemisphere with a radius of 1.5 mm[17,37] and then milled with a zirconia disk using a five-axis milling machine (DWX-51D, Roland DGA). Upon completion of the sintering process, the abraders were uniformly polished following the established protocol using a zirconia restoration-polishing kit (ZiLMaster, Shofu Dental) and a low-speed handpiece operating at approximately 10,000 rpm.[36,38] This polishing procedure was carried out by an experienced dental technician with more than a decade of expertise in the field. Wear tests were conducted using a chewing simulator (CS-4.8, SD Mechatronik). The abraders were positioned on the upper holder, whereas the printed specimens were placed on the lower holder in the water chamber of the chewing simulator. The specimens were placed on the masticatory simulator so that the orientation of the 3D-printed layer against wear direction was the same within each group (Fig 3). The masticatory simulation was conducted with a 0.8-Hz repetitive motion of 5-mm vertical downward movement, a horizontal movement of 2 mm, and a vertical load of 5 kg. During masticatory simulation, the resin specimens were thermocycled in distilled water at cold and hot bath temperatures of 5°C and 55°C, respectively. A masticatory simulation of 60,000 cycles was performed for each specimen, which was reported to be equivalent to a clinical use of 3 months.[17,39]

Evaluation of Wear Volume Loss and Surface Morphology

After the wear test, all specimens were scanned using a desktop scanner (D1000, 3Shape) with 5-μm accuracy (ISO 12836[40]). Then, the scanned data were imported into 3D metrology software (Geomagic Control X, version 2018.1.2, 3D Systems). Using the flat surface of the specimen as a reference point, the 3D object was reverse-engineered with a flat surface before wear. The amount of wear volume loss was obtained by calculating the difference in volume before and after the wear test.[17,41] Furthermore, one representative specimen from each group was randomly chosen using a software-generated (Excel, Microsoft) random number. Finally, thin platinum was coated on the specimen surface with a sputter coater (Q150T-S, Quorum Technologies). The surface morphology of the specimens was observed at ×1,000 magnification at 10 keV using a scanning electron microscope (SEM; Apreo S, Thermo Fisher Scientific).

Statistical Analysis

All statistical data were analyzed using a statistical software program (SPSS version 26.0, IBM). Shapiro-Wilk test indicated that the data were normally distributed in all groups. For the first experiment, a two-way ANOVA was performed for the wear test according to the printing parameters to examine the effect of two factors on the wear volume loss: printing orientation and layer thickness. For the second experiment, which investigated the effects of postpolymerization, one-way ANOVA was performed first to examine significant differences among the seven groups. Subsequently, for the six experimental groups (except the non-postpolymerization group), two-way ANOVA was also performed to analyze the effect of the postpolymerization device and duration. The interaction was examined, and post hoc analyses with Bonferroni correction were used. Statistical significance was set at < .05.

RESULTS

Table 3 presents the wear volume loss according to the printing parameters. Two-way ANOVA indicated that wear volume loss was significantly influenced by printing orientation (df = 2; F = 7.672; $P < .001$). In contrast, the layer thickness did not have a significant effect on wear volume loss (df = 1; F = 0.860; $P = .358$). In addition, no significant interaction was observed between the printing orientation and layer thickness (df = 2; F = 1.955; $P = .151$). The means (95% CIs) for the groups with printing

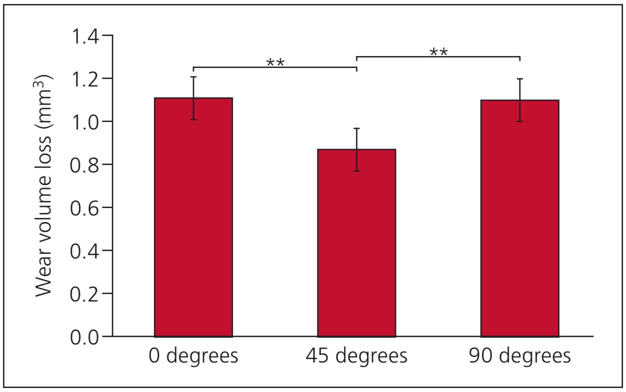

Fig 4 Mean wear volume loss according to the printing orientation degrees (**$P < .01$).

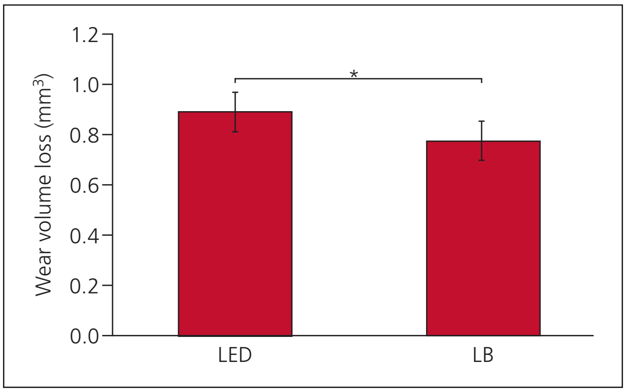

Fig 5 Mean wear volume loss according to the postpolymerization devices (*$P = .04$).

orientations of 0, 45, and 90 degrees were estimated as 1.109 (1.011 to 1.207), 0.870 (0.772 to 0.968), and 1.100 (1.002 to 1.197) mm^3, respectively (Fig 4). The 45-degree–oriented group showed the lowest wear volume loss ($P < .01$). No significant difference was observed between the 0- and 90-degree–oriented groups ($P = 1.000$).

For the second wear test regarding postpolymerization variables (Table 4), one-way ANOVA revealed a significant difference among all groups (df = 6; F = 29.211; $P < .001$). The non-postpolymerization group showed significantly greater wear volume loss than the other groups ($P < .001$). No significant differences were observed among the other postpolymerized groups ($P > .05$). Two-way ANOVA was conducted to compare the differences among the postpolymerized groups, except for the non-postpolymerization group. Two-way ANOVA showed that the postpolymerization devices significantly influenced the wear volume loss of the specimens (df = 1; F = 4.422; $P = .04$). The mean (95% CI) wear volume loss for the LED group was 0.891 (0.813 to 0.969) mm^3, which was significantly higher than that of the LB group, which had a loss of 0.776 (0.698 to 0.854) mm^3 (Fig 5). In contrast, the postpolymerization duration had no significant influence on the wear volume loss (df = 2; F = 2.186; $P = .122$). There was no significant interaction between these two factors (df = 2, F = 0.081, $P = .923$).

SEM images of the specimen surface after the wear test are shown in Figs 6 and 7. The worn surfaces of all specimens exhibited compression and crushing. No distinct differences were observed between groups according to printing and postpolymerization parameters.

DISCUSSION

In this in vitro study, the printing orientation and postpolymerization devices showed a statistically significant influence on the wear resistance of the tested resin specimens. Therefore, the null hypothesis of the present study was partially rejected. After masticatory simulation, the wear volume loss of the specimens with a 45-degree printing orientation were significantly lower than those in the 0- and 90-degree groups. Furthermore, the resin specimens postpolymerized with LB exhibited higher wear resistance than those postpolymerized with LED.

Table 3 Mean Wear Volume Loss According to Printing Parameters

Printing orientation	Layer thickness 50 µm	100 µm
0 degrees	1.208 ± 0.196 mm^3	1.010 ± 0.159 mm^3
45 degrees	0.886 ± 0.232 mm^3	0.854 ± 0.164 mm^3
90 degrees	1.063 ± 0.268 mm^3	1.136 ± 0.265 mm^3

Data are presented as mean ± SD.

Table 4 Mean Wear Volume Loss According to the Postpolymerization Time and Device

Postpolymerization time	Device LED	LB	P*
0 min	1.872 ± 0.338^b		< .001
5 min	0.970 ± 0.293^a	0.854 ± 0.215^a	
15 min	0.848 ± 0.236^a	0.706 ± 0.160^a	
30 min	0.856 ± 0.205^a	0.768 ± 0.125^a	

Data are presented in mm^3 as mean ± SD values. Different lowercase letters indicate a significant difference.
*One-way ANOVA.

This study demonstrated that printing orientation had a significant influence on the wear volume loss of the 3D-printed resin. The lowest wear volume loss was observed at specimens with a 45-degree printing orientation. Previous studies have shown that the mechanical properties of printed resins are significantly influenced by the printing orientation.[18,23,28] The compressive strength,[18] flexural strength,[23,27] and fracture strength[28] of the printed resin were reported to be the

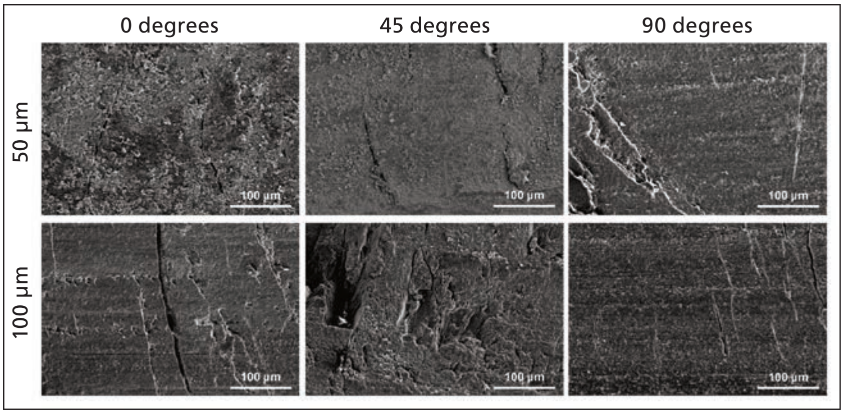

Fig 6 SEM images of the specimen surface according to the printing parameters after masticatory simulation (original magnification ×1,000).

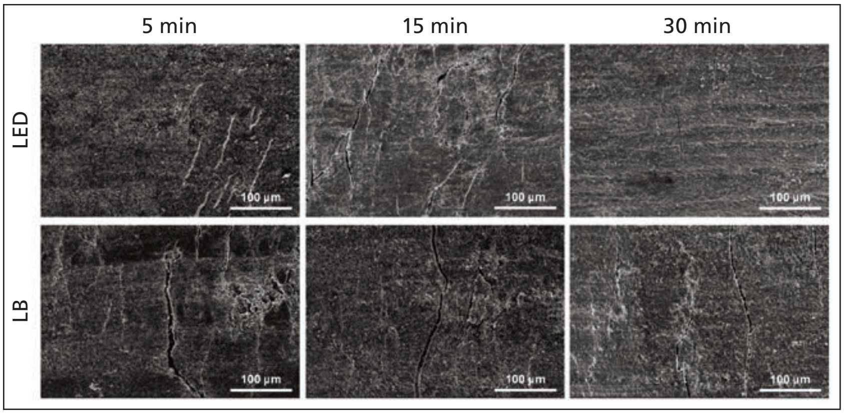

Fig 7 SEM images of the specimen surface according to the postpolymerization strategies after masticatory simulation (original magnification ×1,000).

highest when printed at 0 degrees compared to those printed at other build angles. This indicates that applying a load perpendicular to the vertically stacked layers (done by printing at 0 degrees) helps achieve the most potent mechanical properties. However, in the present study, the wear volume loss was lowest when the printing orientation was 45 degrees compared to that at 0 and 90 degrees. This is believed to be caused by the antagonist moving downward and then laterally in the wear test. The layers stacked at 45 degrees form a stepwise surface of the printed resin, and the microstructure may contribute to wear resistance. In addition, similar to the fact that the 0-degree printed stacked layers can help resist a vertical load, the 45-degree–oriented layers may also impart a resistance element to the antagonist's lateral slide. Thus, while printing at 0 degrees may produce resin restorations with the highest strength, clinicians should consider that printing at 45 degrees may result in higher resistance against wear.

The results of the present study showed no significant difference in the wear resistance between resins printed with layer thicknesses of 50 and 100 μm. Printers usually adapt to printing thickness by changing the light exposure time. The printer software used herein increased the exposure time from 1 to 1.28 seconds in association with increasing the layer thickness from 50 to 100 μm. This may be the reason for the lack of significant difference in wear between the 50- and 100-μm groups. Scherer et al[32] also reported that the layer thickness of the printed resin did not affect the mechanical properties of the printed resin. In addition, in a previous study that used the same resin type and 3D printer as the present study,[32] no significant difference in flexural strength was found upon comparing printed resins of different layer thicknesses (10, 25, 50, 75, 100, and 125 μm). Similarly, in the present study, the layer thickness did not significantly affect wear resistance. However, as a study on the outcomes of a fused deposition modeling-type printer reported that the layer thickness affects the mechanical properties of resin,[19] it should be considered that the results may vary depending on the 3D-printing type and material.

The present study, which compared postpolymerization for different periods using two postpolymerization devices, showed a difference in wear volume loss depending on the device. This is consistent with the results of previous studies that reported that the mechanical properties of 3D-printed resin may vary depending on the type of postpolymerization device.[24,25,30] In the present study, a greater amount of wear volume loss was observed when polymerized with LED than with LB, which may be due to the difference in the light source, and more specifically the amount of energy delivered to the monomers. The LED device had a power output of 80 W, while the LB device, which contained 12 separate 18-W lamps, is considered to have a light power of up to 216 W. This difference in light power might have influenced the results. Previous studies have also reported that a postpolymerization device using LED technology produces a resin specimen with relatively low hardness.[24,25,30] However, it was reported that the flexural strength after using an ultraviolet LED postpolymerization device did not differ significantly from that after using an ultraviolet LB postpolymerization device.[30,31]

Therefore, various factors should be considered when selecting a postpolymerization device.

No significant difference in wear volume was observed loss according to the postpolymerization times of 5, 15, and 30 minutes. In a previous study that compared the results of 30, 60, 90, and 120 minutes of postpolymerization of 3D-printed denture base resin, it was reported that the flexural strength significantly increased with increasing postpolymerization time.[27] However, because the study reported that most groups showed sufficient flexural strength to meet ISO standards,[27] an excessively long time may be unnecessary for chairside fabrication in the clinic. In contrast, Scherer et al[26] compared postpolymerization times (25, 30, 35, 40, and 45 minutes) using LB postpolymerization and reported that the highest fracture strength and average flexural strength were observed at 25 minutes postpolymerization. Further, Soto-Montero et al[33] compared the results of postpolymerization times (5, 10, 15, and 20 minutes) of various 3D-printed resins and reported that the flexural strength of the evaluated resins reached a plateau after 5 or 10 minutes of postpolymerization. These results, which show that sufficient mechanical properties can be obtained with a short postpolymerization time, are consistent with the results of the present study, which showed no difference in the wear resistance at 5, 15, and 30 minutes postpolymerization. Based on the findings of the previous[33] and present studies, it may be inferred that the mechanical properties attained through a 30-minute postpolymerization process can be achieved with a shorter postpolymerization time. However, because non-postpolymerized resin showed significantly lower wear resistance, postpolymerization of at least 5 minutes should be performed. In addition, other factors (such as cytotoxicity, dimensional accuracy, and color stability) should also be considered when selecting the postpolymerization time.[30,31,33]

The present study exhibited several strengths, notably the incorporation of oral masticatory simulations. These simulations employed 60,000 cycles to closely mimic the typical usage duration of provisional restorations in a clinical setting. Thermal cycling, which contributed to additional artificial aging, was conducted during masticatory simulation; thus, the aging factor was also included. However, this study has limitations due to its in vitro design, which utilized flat specimens in a two-body wear test. The intention was to simplify the load direction to evaluate the wear resistance of the printed resin material. However, actual clinical situations involve complex, multidirectional loads on anatomically shaped teeth, resulting from food and chewing patterns. Consequently, translating the findings on printing orientation to clinical practice may be challenging. Additionally, results in the actual oral environment might differ due to factors such as saliva, food, and antagonist type. Further, the present study only assessed one type of printed interim restoration material and a DLP-type 3D printer, which may limit the generalizability of the findings. Therefore, further clinical studies with more types of materials are required to confirm the results of the present study.

CONCLUSIONS

Within the limitations of the present study, the following conclusions were drawn:

1. The wear resistance of the printed resin was significantly greater when printed at a build angle of 45 degrees compared to that at 0- and 90-degree printing orientations.
2. The printed resin postpolymerized with the ultraviolet LB device showed less wear volume loss than specimens postpolymerized with the ultraviolet LED device.
3. The layer thickness and postpolymerization time did not significantly affect the wear resistance of the printed resin. However, the non-postpolymerized resin showed a lower wear resistance compared to the postpolymerized specimens.

Thus, interim resin restorations printed at a build angle of 45 degrees and postpolymerized for at least 5 minutes with the ultraviolet LB device can be chosen to provide greater wear resistance and fabrication time efficiency.

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