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Original Research Article

Effects of Build Orientation and Post-polymerization Method on the Mechanical Properties of a 3D-printed Permanent Resin Material

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ABSTRACT

Aim: The purpose of this study was to investigate how different build orientations and post-polymerization protocols influence the microhardness and biaxial flexural strength (BFS) of 3D-printed permanent resin material.

Materials and Methods: Ninety disc-shaped specimens were manufactured using a digital light processing (DLP) 3D printer at three build orientations (0°, 45°, 90°). Specimens were post-processed using either a desktop curing unit (FC) or a handheld polywave light emitting diode (LED) light-curing unit (LCU). Microhardness (VHN) was measured using a Vickers microhardness tester, and BFS was evaluated using a piston-on-three-ball test. Two-way ANOVA and Tukey HSD tests were used for statistical analysis (α = .05).

Results: The post-polymerization method significantly affected BFS ($p < .001$), with the LCU group exhibiting higher strength (336.8 ± 81.6 MPa) than the FC group (255.2 ± 83.3 MPa). Build orientation also had a significant influence on BFS ($p < .001$); the 0° groups showed higher values than the 45° and 90° groups. Microhardness was significantly influenced by the post-polymerization method ($p = .04$), whereas build orientation had no significant effect on VHN values (p=63).

Conclusion: Both build orientation and post-polymerization method influenced the mechanical behavior of the 3D-printed resin, particularly its BFS. The handheld polywave LCU provided superior flexural performance compared with the desktop curing unit, suggesting that it may serve as a reliable alternative for post-polymerization of 3D-printed dental materials. Optimizing printing and post-polymerization parameters is essential to enhance the mechanical reliability of additively manufactured restorations.

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INTRODUCTION

The continuous progress of computer-aided design and manufacturing (CAD/CAM) systems has substantially reshaped various areas of dental practice, especially in prosthodontics and restorative dentistry. Subtractive and additive manufacturing -also known as milling and 3D printing- constitute the fundamental methods of these technologies.[1] While subtractive manufacturing (SM) offers standardized material quality through milling of industrially prefabricated blocks, it is limited by material waste and geometric constraints.[2,3] In contrast, additive manufacturing (AM) enables layer-by-layer fabrication with minimal waste, allowing efficient production of intricate designs and multiple units simultaneously.[4–6]

The dental AM workflow comprises three main phases: digital design, printing, and post-processing. Among the printing parameters, build orientation is one of the most critical factors influencing the internal structure and mechanical behavior of printed objects.[7] The orientation of the layers relative to the direction of applied forces affects not only the bonding strength between layers but also the surface quality, dimensional accuracy, and overall durability of the printed restoration.[8] Variations in build angle can

therefore lead to anisotropic properties, resulting in differences in flexural strength and surface hardness depending on the printing direction.[9,10]

Following the printing process, post-processing steps such as cleaning and post-polymerization have a significant impact on the mechanical and biological performance of printed resins.[11] The post-polymerization process is generally conducted using light sources that emit at specific wavelengths to advance the polymerization of the printed material from its initial green state to a completely cured, stable form.[11–13] In the literature, desktop post-polymerization devices are commonly used for this purpose, offering controlled light intensity and exposure time that ensure sufficient polymerization.[14–16] Recently, the utilization of portable light-curing units (LCUs) has been suggested as an effective choice, providing mobility, decreased processing time, and possibility for chairside applications.[11,12]

Conventional LCUs emit light within a wavelength range that matches the absorption spectrum of camphorquinone, the primary photoinitiator in most resin-based materials.[17] In recent years, advanced polywave light-emitting diode (LED) LCUs capable of emitting multiple wavelength bands have been developed to effectively activate different photoinitiator systems.[18,19] Such devices may also be applicable for the post-polymerization of 3D-printed resins, potentially offering a practical, time-efficient, and chairside alternative to traditional desktop curing units.[12,20]

Therefore, the aim of this study was to evaluate the effects of two key parameters -build orientation and post-processing protocols- on the mechanical properties of 3D-printed permanent resin material. The null hypothesis was that neither the use of different polymerization devices nor variations in build orientation would significantly affect the mechanical properties -microhardness and biaxial flexural strength- of the 3D-printed resin material.

MATERIALS AND METHODS

In this *in vitro* study, a total of 90 disc-shaped specimens (14 × 1.8 mm) were printed from a permanent crown resin with nanoceramic fillers (Power Resin C&B Ceramic; Dentafab, Türkiye) (Table 1). An a priori power analysis (G*Power 3.1; Düsseldorf University, Germany) was performed for a two-way ANOVA including both main effects and their interaction. Assuming a medium-to-strong effect size (Cohen's f = 0.35), an α level of 0.05, and a statistical power of 0.80, a minimum of 15 specimens per subgroup was required.

Specimens were designed using CAD software (Exocad, Germany), exported in STL format, and processed in Dentafab platform software (Dentafab, Türkiye). Discs were positioned to avoid contact during printing. Three print build orientations were used: 0°, 45°, and 90°, with 30 specimens printed per orientation in separate batches. Printing was performed using a digital light processing (DLP) printer (SEGA LFP-PRO; Dentafab, Türkiye) with a 50 µm layer thickness and a 385 nm light source.

All 90 printed specimens were randomly assigned (https://www.randomizer.org) into two post-polymerization groups: a control group (FC) using a desktop curing unit (Form Cure; Formlabs, USA) and an experimental group (LCU) using a handheld polywave LED light-curing unit (Valo; Ultradent Products, USA). Each group contained 15 discs per build orientation (0°, 45°, 90°). The study design was presented in Figure 1.

Specimens in the FC group were ultrasonically

Table 1. 3D-printed resin used in the study.

Material	Type	Composition	Manufacturer	Lot Number
Power Resin C&B Ceramic	3D-printed nanoceramic-filled permanent crown resin	Esterification products of 4,4'-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (50–55%), ethyl phenyl (2,4,6-trimethylbenzoyl) phosphinate (1–5%), dental glass (20–30%)	Dentafab, 3BFAB Technology, Türkiye	MD1108250818004

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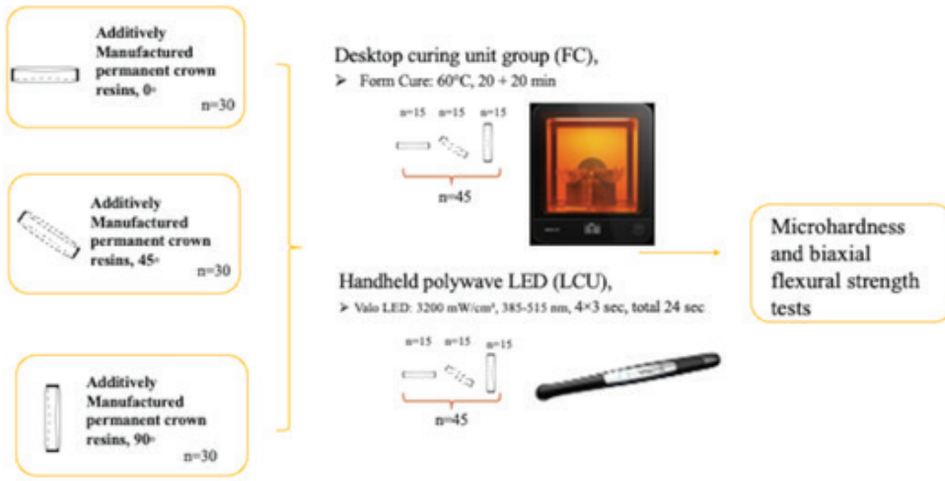


Figure 1. Study design.

cleaned (Form Wash; Formlabs, USA) in 99% isopropyl alcohol for 5 minutes and dried with compressed air. Curing was performed in a desktop curing unit at 60°C for 20 minutes on each side (supports in place for the first cycle, removed for the second), following the manufacturer's instructions. For the LCU group, specimens were cleaned in 99% isopropyl alcohol for 5 minutes, air-dried, and polymerized using a handheld polywave LED LCU from both top and bottom surfaces in four cycles of 3 seconds each (total exposure: 24 seconds) in Xtra Power mode, following the protocol described by Kim *et al*.[12], who reported improved microhardness and biaxial flexural strength with bidirectional light curing for a total of 24 seconds. The device emitted a broad wavelength spectrum (385–515 nm) with an irradiance of 3200 mW/cm². After every five specimens, irradiance was verified using a radiometer (Model 100; Demetron/Kerr, Danbury, USA) to ensure consistency.

All specimens were kept in distilled water at 37 °C for 24 hours prior to testing. The upper and lower surfaces were sequentially polished under continuous water flow using silicon carbide abrasives in 800-, 1200-, and 2000-grit sequences. Specimen dimensions were verified with a digital caliper (Micrometers 293-82130; Mitutoyo).

Vickers microhardness was measured using a microhardness tester (HMV-2000; Shimadzu Corporation, Japan) with a 300-gf load applied for 15 seconds. Indentations were made with a 10 μm diamond tip at 0.25 mm spacing along a 5.6 mm test line. Measurements were taken from three regions of each specimen at 45° intervals, and the average of these readings was used for analysis. Vickers hardness number (VHN, kg/mm²) was calculated according to the formula:

$$VHN = 1854.4 \times P / d^2$$

where P is the applied load (g) and d is the mean diagonal length of the indentation (mm).

Biaxial flexural strength (BFS) of the specimens was determined using a piston-on-three-ball setup in accordance with ISO 6872 standards.[21] For each test, three supporting steel spheres were positioned 120° apart on an 11-mm diameter circle. The specimens were loaded until fracture in a universal testing machine (Testometric M270, UK) at a crosshead speed of 1 mm/min, using a flat-ended piston with a 1.5-mm diameter. To prevent any influence of the Vickers indentations on subsequent biaxial flexural strength testing, the surface containing the microhardness indentations was always positioned facing upward during the BFS test, away from the critical tensile zone. The BFS value (σ, MPa) was then calculated using the following formula:

$$BFS = -0.2387P(X-Y) / b^2$$

$$X = (1+v)\ln(r_2/r_3)^2 + [(1-v)/2](r_2/r_3)^2$$

$Y = (1+v)[1 + \ln(r_1/r_3)^2] + (1-v)(r_1/r_3)^2$, in this equation, r_1 corresponds to the radius of the supporting circle (5.5 mm), r_2 represents the radius of the loading piston (0.75 mm), and r_3 denotes the radius of the test specimen. The specimen thickness is expressed

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as b, the Poisson's ratio was taken as 0.25, and P refers to the fracture load recorded in Newtons.

All statistical evaluations were performed in SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed with the Shapiro–Wilk test, while variance homogeneity was confirmed through Levene's test. Since the assumptions for parametric testing were satisfied, a two-way analysis of variance (ANOVA) was conducted to evaluate the effects of post-polymerization method (two levels: FC and LCU) and build orientation (three levels: 0°, 45°, and 90°) as fixed factors, as well as their interaction, on microhardness and biaxial flexural strength. When significant effects were detected, pairwise comparisons were performed using Tukey's honestly significant difference (HSD) post hoc test. The significance level was set at $\alpha = 0.05$.

RESULTS

The mean and standard deviation values of VHN and BFS for each post-polymerization group (FC and LCU) are descriptively presented in Table 2. The LCU group exhibited slightly higher VHN values (22.8 ± 1.4) compared to the FC group (22.2 ± 1.6). The LCU group (336.8 ± 81.7 MPa) showed higher BFS values than the FC group (255.2 ± 83.4 MPa).

Mean VHN and BFS values according to build orientation are descriptively summarized in Table 3. The specimens printed at 0° (366.9 ± 83.4 MPa) exhibited a higher BFS value than those printed at 45° (269.1 ± 76.3 MPa) and 90° (252.1 ± 71.6 MPa).

The effects of build orientation and post-polymerization method on subgroups' VHN and BFS values, along with pairwise comparisons based on Tukey's HSD test, are presented in Table 4. The specimens printed at LCU-0° (23.7 ± 1.19) exhibited a higher VHN value than those printed at LCU-90° (21.9 ± 0.5) and FC-0° (21.1 ± 1.5). For BFS, the highest values were obtained in the LCU-0° group (402. ± 71.6 MPa), followed by FC-0° (331.8 ± 81.4 MPa), while the lowest mean value was recorded in the FC-45° group (214.7 ± 47.2 MPa).

The two-way ANOVA revealed the effects of the post-polymerization method (two levels: FC and LCU) and build orientation (three levels: 0°, 45°, and 90°), as well as their interaction, on the outcome variables VHN and BFS. Complete ANOVA outputs, including degrees of freedom and F statistics, are presented in Table 5. The post-polymerization method significantly affected both VHN ($p = .04$) and BFS ($p < .001$), whereas build orientation significantly influenced BFS ($p < .001$) but not VHN ($p = .63$). A significant interaction between post-polymerization method and build orientation was observed for VHN ($p < .001$), whereas no significant interaction was found for BFS ($p = .38$). The interaction effects are illustrated in Figures 2 and 3.

Table 2. Mean (±SD) values of VHN and BFS according to post-polymerization method.

	VHN Mean ± SD	BFS (MPa) Mean ± SD
FC	22.2 ± 1.6	255.2 ± 83.4
LCU	22.8 ± 1.4	336.8 ± 81.7

VHN, Vickers hardness number; BFS, biaxial flexural strength; MPa, megapascals; SD, standard deviation; FC, desktop polymerization unit group; LCU, light curing unit group.

Table 3. Mean (±SD) VHN and BFS values according to build orientation.

	VHN Mean ± SD	BFS (MPa) Mean ± SD
0°	22.5 ± 1.9	366.9 ± 83.4
45°	22.6 ± 1.4	269.1 ± 76.3
90°	22.3 ± 1.3	252.1 ± 71.6

VHN, Vickers hardness number; BFS, biaxial flexural strength; MPa, megapascals; SD, standard deviation.

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Table 4. Mean (±SD) subgroups' VHN and BFS values according to build orientation and post-polymerization method with Tukey HSD pairwise comparisons.

Group	0°	45°	90°
VHN			
FC	21.1 ± 1.5^{c}	22.7 ± 1.2^{ab}	22.5 ± 1.6^{ab}
LCU	23.7 ± 1.1^{b}	22.5 ± 1.5^{abc}	21.9 ± 0.5^{ac}
BFS (MPa)			
FC	331.8 ± 81.4^{C}	214.7 ± 47.2^{A}	219.2 ± 59.6^{AB}
LCU	402 ± 71.6^{D}	323.5 ± 59^{C}	285 ± 68.8^{BC}

Different lowercase letters within each row indicate statistically significant differences in microhardness ($p < .05$). Different uppercase letters within each row indicate statistically significant differences in BFS ($p < .05$). VHN, Vickers hardness number; BFS, biaxial flexural strength; MPa, megapascals; SD, standard deviation; FC, desktop polymerization unit group; LCU, light curing unit group.

Table 5. Results of two-way ANOVA evaluating the effects of post-polymerization method, build orientation, and their interaction on VHN and BFS.

	df	F (VHN)	p (VHN)	F (BFS)	p (BFS)
Post-polymerization method	1	4.34	.04	34.93	<.001
Build Orientation	2	0.47	.63	26.82	<.001
Interaction (Post-polymerization method × Build orientation)	2	12.80	<.001	0.98	.38
Error	84	—	—	—	—

VHN, Vickers Hardness Number; BFS, biaxial flexural strength; df, degrees of freedom; F, F statistic obtained from two-way ANOVA.

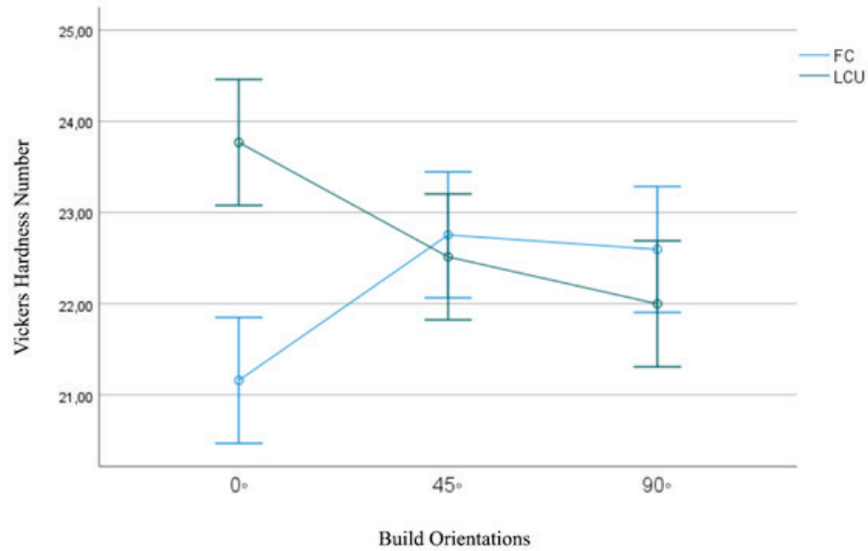


Figure 2. Interaction plot showing the combined effects of build orientation and post-polymerization method on Vickers microhardness (VHN). Error bars represent 95% confidence intervals ($p < 0.001$).

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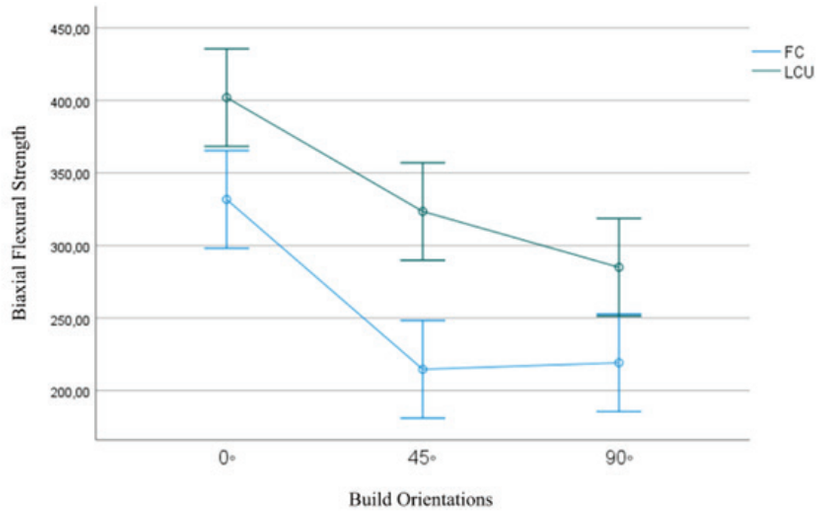


Figure 3. Interaction plot showing the combined effects of build orientation and post-polymerization method on biaxial flexural strength (BFS). Error bars represent 95% confidence intervals (p = 0.38).

DISCUSSION

Based on the findings of this study, the null hypotheses were partially rejected. Both the post-polymerization method and build orientation significantly influenced the biaxial flexural strength of the 3D-printed resin material, whereas microhardness was significantly affected by the post-polymerization method but not by build orientation.

The results of this study demonstrated that build orientation significantly influenced the BFS value of the 3D-printed permanent resin material, with specimens printed at 0° exhibiting the highest BFS values, followed by those printed at 45° and 90°. These findings suggest that build orientation plays a dominant role in determining flexural performance. Similar trends have been documented in previous studies, where specimens printed parallel to the build platform demonstrated superior mechanical strength compared with those fabricated at oblique or vertical angles.[8,22] This behavior can be attributed to the anisotropic structure inherent to layer-by-layer fabrication. When the layers are aligned parallel to the direction of the applied load, as in the 0° orientation, stress is distributed more uniformly across the printed planes, resulting in higher resistance to fracture. In contrast, the 45° and 90° orientations expose the interlayer interfaces to tensile stresses, leading to premature crack initiation and reduced mechanical performance.[8,23] However, some studies have reported opposite findings, indicating that specimens printed at 90° exhibited superior mechanical properties compared with those printed at 0°.[9,24] Such discrepancies may be attributed to several factors, including the type of 3D printer, the resin's chemical composition, the post-polymerization protocol, and the mechanical testing parameters employed. These variations across studies highlight the complexity of additive manufacturing and emphasize the importance of further investigating the influence of build orientation on the mechanical performance of 3D-printed dental materials.

In the present study, no statistically significant differences in microhardness were observed among the groups, regardless of build orientation. This finding is consistent with the results of de Castro *et al*.[9], who also reported that the printing direction had no significant effect on the surface hardness of 3D-printed resins. One possible explanation for this behavior is that surface hardness is primarily governed by the outermost cured layers, which receive sufficient light exposure during printing and post-polymerization, leading to a similar degree of polymerization across orientations. Because the adhesive strength between successive printed layers is lower than the strength within each layer, the influence of orientation tends to manifest more clearly in flexural strength rather than in hardness.[24]

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The two-way ANOVA revealed significant main effects of both post-polymerization method and build orientation on BFS ($p < .001$). However, no significant interaction was detected between these factors ($p = .38$), indicating that the superiority of the LCU was independent of build orientation. The present study demonstrated that the post-polymerization technique significantly influenced the flexural properties of the printed resin, with the LCU group exhibiting superior BFS values compared to the FC group. This finding may be attributed to the enhanced irradiance and extensive wavelength spectrum of the polywave LED LCU device, which may efficiently activate various photoinitiator systems and enhance the degree of cross-linking inside the polymer matrix. Recent studies similarly reported that high-intensity or polywave LCUs can achieve mechanical performance comparable to, or in some cases superior to, traditional desktop post-polymerization units under appropriate conditions.[11,12] Bayarsaikhan *et al*.[11] reported that a VALO handheld LCU produced flexural strength values comparable to those from several commercial post-polymerization chambers, indicating that high-intensity LCUs can attain enough polymerization in reduced exposure durations. Similarly, Kim *et al*.[12] indicated that increasing the number of LCU curing cycles enhanced both microhardness and biaxial flexural strength, and that the performance of a handheld LCU was equivalent to that of a normal desktop curing unit when both surfaces of the printed disk were sufficiently irradiated. Based on these findings, the 24-second light-curing protocol used in the present study was selected from scientific evidence rather than arbitrarily. Kim *et al*.[12] demonstrated that bidirectional irradiation for a total of 24 seconds produced consistently high VHN values across both surfaces while also yielding superior BFS compared with shorter exposure durations. This balanced polymerization is essential for achieving reliable mechanical performance throughout the thickness of additively manufactured resin materials while maintaining clinical practicality.

In terms of microhardness, the post-polymerization method significantly affected VHN values, whereas build orientation alone did not produce a significant main effect. However, the significant interaction between the post-polymerization method and build orientation indicates that the influence of the curing device depends on the printing geometry. This is reflected by the LCU-0° subgroup, which exhibited the highest microhardness among all groups. This finding suggests that the effectiveness of light-curing is not determined solely by the light source itself, but also by how light transmission is modulated by the internal layer configuration of the printed material. Differences in optical pathways and energy distribution across build orientations may explain why certain geometric configurations benefit more from high-intensity polywave irradiation. Overall, these results indicate that contemporary polywave LCUs may serve as a practical alternative to conventional desktop post-polymerization units.

One of the limitations of this study is that only a single resin material and one type of 3D printing technology were evaluated, which restricts the generalizability of the findings to other resin compositions or printing systems. Another limitation is that the specimens were not exposed to any aging procedures, which could alter the mechanical properties and better simulate intraoral conditions. In addition, although the degree of conversion is a critical determinant of the physical behavior of photopolymerized resins, this parameter was not assessed in the present study. Further studies should investigate different 3D printing technologies and resin formulations, incorporate artificial aging protocols, and evaluate the degree of conversion using Fourier-transform infrared (FTIR) or Raman spectroscopy to provide a more comprehensive understanding of how polymerization efficiency influences mechanical performance.

CONCLUSION

Within the limitations of this study, both build orientation and post-polymerization method were found to influence the mechanical performance of the 3D-printed permanent resin material. While build orientation significantly affected biaxial flexural strength, it had no impact on microhardness. The handheld polywave LED LCU produced biaxial flexural strength values superior to those of the desktop curing unit, indicating that it may serve as an effective alternative for post-polymerization of 3D-printed dental materials. These findings highlight the importance of optimizing printing and post-

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processing parameters to enhance the mechanical reliability of additively manufactured restorations.

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3D Baskılı Kalıcı Rezin Materyalin Mekanik Özellikleri Üzerinde Basım Açısı ve Post-Polimerizasyon Yönteminin Etkileri

ÖZET

Amaç: Bu çalışmanın amacı, farklı basım açıları ve post-polimerizasyon protokollerinin, 3D baskı ile üretilmiş kalıcı rezin materyalin mikrosertlik ve çift eksenli eğilme direnci (BFS) üzerindeki etkilerini değerlendirmektir.

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Gereç ve Yöntemler: Doksan adet disk şeklinde örnek, dijital ışıkla şekillendirme (DLP) tipi bir 3D yazıcı kullanılarak üç farklı baskı açısında (0°, 45°, 90°) üretildi. Örnekler, ya masaüstü bir polimerizasyon cihazı (FC) ya da taşınabilir poliwave ışık yayan diyot (LED) esaslı bir ışık cihazı (LCU) ile kürlendi. Mikrosertlik (VHN), Vickers mikrosertlik test cihazı ile; BFS ise piston-üç-bilye testi kullanılarak değerlendirildi. İstatistiksel analiz için iki yönlü ANOVA ve Tukey HSD testleri uygulandı (α = .05).

Bulgular: Post-polimerizasyon yöntemi BFS üzerinde anlamlı bir etki gösterdi (p < .001); LCU grubu (336.8 ± 81.6 MPa), FC grubuna (255.2 ± 83.3 MPa) kıyasla daha yüksek BFS değerleri sergiledi. Basım açısı da BFS üzerinde anlamlı bir etki oluşturdu (p < .001); 0° basım açısındaki örnekler, 45° ve 90° gruplarından daha yüksek direnç gösterdi. Mikrosertlik değerleri post-polimerizasyon yönteminden anlamlı düzeyde etkilenmiştir (p = .04), ancak basım açısının mikrosertlik üzerinde anlamlı bir etkisi bulunmamıştır (p = .63).

Sonuç: Hem basım açısı hem de post-polimerizasyon yöntemi, 3D baskılı rezin materyalin mekanik davranışını, özellikle BFS değerlerini etkilemiştir. Taşınabilir poliwave LCU, masaüstü polimerizasyon cihazına kıyasla daha yüksek eğilme direnci sağlamış olup, 3D baskılı dental materyallerin post-polimerizasyon işlemi için güvenilir bir alternatif olabileceğini göstermektedir. 3D baskı restorasyonlarının mekanik güvenilirliğini artırmak için baskı ve post-polimerizasyon parametrelerinin optimize edilmesi önemlidir.

Anahtar Kelimeler: Sertlik testleri; Mekanik kavramlar; Polimerizasyon; Üç boyutlu üretim

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