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Effect of DLP and LCD Printing and Nitrogen Post-Curing on the Performance of 3D-Printed Resins

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Abstract

This study assessed the effects of printing technology (DLP vs. LCD), post-curing in a nitrogen environment and the interaction between these two factors on the compressive, tensile and flexural strengths of a 3D-printed dental resin. Specimens were virtually designed using Exocad dental CAD software and printed using two dissimilar printing technologies: a Digital Light Processing (DLP) printer (Shining 3D) and a Liquid Crystal Display (LCD) printer (Sol). Thereafter, the specimens were post-cured in either a conventional atmosphere or a nitrogen gas atmosphere. The specimens were then tested for compressive strength (in accordance with ISO 604), tensile strength (in accordance with ISO 527-1) and flexural strength (in accordance with ISO 4049). The main factor that significantly affected all three tested mechanical parameters was the printing technology. While the Shining 3D printer (DLP) demonstrated superior compressive strength, the Sol printer (LCD) yielded better performance in terms of both tensile and flexural strengths. Post-curing the specimens in a nitrogen-based environment presented a non-significant effect on the mechanical performance of the tested material. Additionally, the interaction between printing technology and curing atmosphere was not statistically significant. Within the limitations of this *In Vitro* study, printing technology is the predominant factor influencing the mechanical properties of the tested dental resin. DLP systems are preferred when compressive strength is the primary concern. Conversely, LCD-based printers are recommended when the priority is tensile and flexural strengths. The use of a nitrogen post-curing atmosphere did not improve the tested parameters.

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Introduction

Additive manufacturing in dentistry, also known as 3D printing has gained increased popularity in everyday clinical practice. It is adopted in diverse applications such as the fabrication of orthodontic aligners, temporary crowns, surgical guides and indirect restorations. This technique provides many benefits such as high production speed, dimensional accuracy and high-quality surface finish [1].

Currently, a variety of photopolymerization systems are implemented in clinical and laboratory applications. Digital Light Processing (DLP) and Liquid Crystal Display (LCD) are two of the most widely employed techniques for 3D printing. While these technologies are based on the principle of layer-by-layer curing for the object to be printed, they use distinct light delivery techniques to cure the dental resin. In DLP-based systems, a digital micromirror device (DMD) is employed to project a specific light pattern across the entire resin layer. On the other hand, LCD printers depend on an array of ultraviolet (UV) LEDs shining through an LCD panel, which acts as a mask to block light in non-print areas and allows it to pass through where curing is required [2]

This disparity in light intensity and pixel generation between these two methods might affect the polymerization sequence, subsequently altering the mechanical performance of the printed restorations [3]. In both techniques, a post-curing procedure is executed in a UV light chamber, which promotes the degree of resin

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polymerization. This step is critical as it plays a significant role in the biocompatibility, dimensional stability and mechanical behavior of the printed restorations. The presence of atmospheric oxygen induces the formation of an under-cured oxygen inhibition layer (OIL) that might jeopardize the mechanical performance and structural integrity of the restoration. The use of inert nitrogen (N_2) is highly advocated to suppress the formation of the OIL and to increase the degree of conversion, which in turn enhances the mechanical properties of the restorations [4,5].

There is a clear need to study the combined effects of printing technology and the presence of N_2 on the mechanical characteristics of 3D-printed resins. Therefore, the aim of this in vitro study is to investigate the effect of printing technology (DLP vs. LCD) and the role of using nitrogen atmosphere during post-curing on the compressive, tensile, and flexural strengths of a commercially available 3D-printed dental resin. The null hypotheses tested are:

(1) The printing technology (DLP vs. LCD) has no significant effect on the tested mechanical parameters of the dental resin.

(2) The application of a nitrogen atmosphere during post-curing does not significantly affect the compressive, tensile, and flexural strengths of the material.

(3) There is no interaction effect between printing technology and post-curing atmosphere on the mechanical properties of the tested resin.

Materials and Methodos

Study Design and Specimen Preparation

Specimens were 3D-printed using a tooth-colored dental resin (Shining 3D Ceramic CB Resin, Shade CB12; lot number: 20250218-19, Shining 3D, Hangzhou, China). Standardized samples for each test were virtually designed using Exocad dental CAD software (Exocad GmbH, Darmstadt, Germany). The total number of the specimens was 120. These were divided into three groups according to their geometry (following the ISO standards for each mechanical test):

1. **Compressive Strength**: Cylindrical specimens measuring 5 mm in diameter and 10 mm in height, designed in accordance with ISO 604 [6].
2. **Tensile Strength**: Dog-bone-shaped specimens measuring 75 mm in length, 5 mm in width and 2 mm in thickness, designed in accordance with ISO 527-2 [7].
3. **Flexural Strength**: Rectangular bar specimens measuring 25 mm in length, 2 mm in width, and 2 mm in thickness, designed in accordance with ISO 4049 [8].

Two distinct types of 3D printers were involved in the printing process: a DLP printer (AccuFab-F1; SHINING 3D, Hangzhou, China) and an LCD printer (SOL; Ackuretta Technologies, Taipei, Taiwan). The printing procedure followed standardized parameters (a layer thickness of 50 µm and a 90° print orientation). It is essential to standardize both layer thickness and print orientation, as it has been reported that they significantly affect the accuracy and mechanical properties of the printed material [9,10].

The specimens were randomly allocated into four groups depending on the printer type and post-curing method. The number of the specimens for each group was 30, sub-divided into 10 separate samples for each mechanical test (n=30 per group; n=10 per test):

Group 1: Shining 3D AccuFab-F1 (DLP) + Standard Post-curing (Without N_2).

Group 2: Shining 3D AccuFab-F1 (DLP) + Nitrogen Post-curing (With N_2).

Group 3: Ackuretta SOL (LCD) + Standard Post-curing (Without N_2).

Group 4: Ackuretta SOL (LCD) + Nitrogen Post-curing (With N_2).

Post-Processing and Storage Protocol

A washing protocol was performed on all the specimens using an automatic cleaning device (CLEANI; Ackuretta Technologies, Taipei, Taiwan), to eliminate any residue from the printing procedure that may impede the mechanical performance of the material. This protocol included two 3-minute washing cycles using 99% isopropyl alcohol (IPA) [11].

Subsequently, the specimens were air-dried and post-cured using a UV light-curing unit (Curie Plus; Ackuretta Technologies, Taipei, Taiwan). The post-curing step has been reported to improve polymerization and to alter the mechanical properties of the material [12]. For groups 1 and 3, post-curing procedures were executed under normal atmospheric conditions. In contrast, post-curing procedures for groups 2 and 4 were performed in an inert nitrogen (N_2) environment generated by an integrated nitrogen gas generator (N-finity; Ackuretta Technologies, Taipei, Taiwan) following the manufacturer's instructions [4, 13]. The specimens were then stored in distilled water at 37 °C for approximately 24 hours prior to mechanical testing. This step is critical to simulate the oral environment, in accordance to ISO 4049 testing protocol for dental materials [14].

Mechanical tests were performed using a Universal Testing Machine (UTM) (Tinius Olsen; Horsham, PA, USA). Data were subsequently analyzed using statistical software (IBM SPSS Statistics for Windows, Version 21.0; IBM Corp., Armonk, NY, USA). To determine the effects of printing technology and post-curing conditions and their interaction, a two-way analysis of variance (ANOVA) was conducted using a significance level of 0.05.

Results

The initial step in data analysis was obtaining descriptive statistics including means and standard deviations (SD). The subsequent step involved verifying data normality using the Shapiro-Wilk test and the homogeneity of variances using Levene's test. To assess the effects of printer type, post-curing conditions and their interaction, a two-way analysis of variance (ANOVA) was performed. If any significant differences were detected, post-hoc pairwise comparisons were conducted to identify specific group differences.

Descriptive Statistics

The mean values and standard deviations for the compressive, tensile, and flexural strengths are summarized in Table 1.

Compressive Strength

The two-way analysis of variance (ANOVA) revealed a statistically significant effect of the printing technology on the compressive strength (F = 23.36, p <0.001). Accordingly, specimens produced by Shining 3D printer (104.88 MPa) outperformed those of Sol printer (90.54 MPa). The effect size was 0.393 (measured by partial eta squared), indicating that printing technology accounted for 39.3% of the variance in compressive strength. Conversely, the post-curing nitrogen environment (N_2) did not show a statistically significant effect on the compressive strength (p =0.0645). Similar findings were observed regarding the interaction between the printer type and the curing environment (p >0.05).

Tensile Strength

Printing technology had a statistically significant main effect on tensile strength (F = 9.613, p = 0.004). The mean tensile strength for the Sol printer specimens (54.95 MPa) was higher than the mean for the Shining 3D printer specimens (49.98 MPa) with a partial eta squared of 0.211. In contrast, the use of the nitrogen environment resulted in a non-significant main effect (p = 0.085). Similarly, no significant interaction was observed between printer technology and curing atmosphere (F = 0.214, p = 0.646).

Flexural Strength

As observed for tensile strength, printer type had a significant main effect on the flexural strength (F = 4.362, p = 0.044). The mean achieved by the Sol printer was higher than that of the Shining 3D printer (168.26 MPa vs.158.47 MPa). Neither the curing environment (p=0.810) nor the interaction effect (p=0.335) had a statistically significant effect regarding the bending strength.

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Discussion

This study investigated the effects of printing technology and a post-curing nitrogen environment on the mechanical properties of a 3D-printed dental resin. The results showed that printing technology was the predominant factor affecting the tested parameters. The DLP-based printer (Shining 3D) yielded superior compressive strength, while the LCD printer (Sol) exhibited significantly higher tensile and flexural strengths.

These findings could be attributed to the differences in the light-curing mechanisms of the two technologies (DLP vs. LCD). DLP systems use a digital micromirror device (DMD) to project a high-intensity light beam, leading to the rapid formation of a highly cross-linked polymer network. In such polymer networks, there is a short distance between the polymer chains, and rigid covalent bonds tightly bind them together. When compressive loads are applied, this highly cross-linked polymer network resists deformation by distributing the load across the rigid covalent bonds. In contrast, the high density of covalent bonds limits the ability of the material to stretch or yield when tensile or flexural loads are applied. Hence, the restricted internal movement in response to tensile or flexural loads might increase stress concentration and crack propagation within the material, which promotes brittle fracture [15,16].

On the other hand, LCD technology utilizes an LED array masked by an LCD screen, which produces a more uniform and homogeneous light distribution across the build platform [17,18]. This steady pattern of photopolymerization reduces internal shrinkage stresses during layer formation and provides a more resilient polymer network, which enhances the material's performance under tensile and flexural loads through microscopic chain slipping [16,19]. These findings are strongly consistent with recent literature evaluating the mechanical behavior of various 3D printing technologies. An investigation of the mechanical properties of denture base resins concluded that DLP-printed specimens had a denser polymer network when compared to LCD-printed specimens (3). Moreover, a recent network meta-analysis assessing the flexural strength of provisional dental prostheses reported that DLP printers showed lower performance regarding flexural strength when compared to other systems [20].

The study, concerning the post-curing environment, concluded that the use of a nitrogen gas atmosphere did not significantly enhance the mechanical performance of the specimens ($p > 0.05$). These findings can be explained by understanding the role of nitrogen gas during the post-curing process. The oxygen inhibition layer formed during photopolymerization-which N_2 gas eliminates, promoting complete surface polymerization-affects the superficial layers only. The parameters evaluated in this study (compressive, tensile and flexural strengths) depend more on the macroscopic or bulk properties of the material than on its superficial layers [4,21].

Conclusion

Within the limitations of this in vitro study, printing technology was the primary factor influencing the mechanical performance of the tested resin. DLP printing demonstrated superior compressive strength, whereas LCD printing exhibited higher tensile and flexural strengths. Nitrogen-assisted post-curing did not significantly affect the tested bulk mechanical properties. Further studies are required to determine the clinical significance of these findings.

Limitations

While this study provided certain clinical information regarding the performance of 3d-printed dental resin, several limitations should be acknowledged. First, as it is an *in vitro* study, it does not fully represent the complex and dynamic environment of the oral cavity. There are many factors in such an environment that might affect the long-term mechanical performance of the tested material, such as cyclic masticatory loading, moisture absorption from saliva and thermal cycling. Another limiting factor is the fact that this study tested only a specific type of dental resin and two printers. Accordingly, the findings may not be fully representative to the available types of dental resin and printers combinations.

Conflict of Interest

The authors declare that they have no conflict of interest related to this study, financial or otherwise.

Ethics

Review and approval by an Ethical Committee were not required for this study, as it is an entirely in vitro investigation conducted on commercially available synthetic dental resins and does not involve any human participants, clinical trials, or animal experimentation.

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This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The study was entirely self-funded by the authors.

Authors' contributions

All authors have contributed significantly to this work. The authors were involved in the conceptualization, study design, specimen preparation, mechanical testing, statistical analysis, interpretation of the data, and the drafting and critical revision of the final manuscript.

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Table 1. Descriptive statistics of the mechanical properties (n=10 per group).

Source of Variation	Compressive strength	Tensile strength	Flexural strength
Printer Technology	0.393	0.211	0.108
Curing Environment (N_2)	0.025	0.08	0.002
Interaction (Printer * N_2)	0.034	0.006	0.026

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Table 2. Summary of the partial eta squared values for all mechanical tests. This demonstrates that the main influencing factor on the three tested parameters was printer technology.

Group	Experimental Condition	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)
1	Shining 3D (No N_2)	105.13 ± 7.9	48.19 ± 5.2	155.6 ± 19.82
2	Shining 3D +N_2	104.63 ± 10.86	51.7 ± 5.7	161.32 ± 15.32
3	Sol (No N_2)	87.43 ± 10.05	53.9 ± 5.3	169.98 ± 11.33
4	Sol +N_2	93.65 ± 8.41	55.99 ± 3.71	166.53 ± 11.11

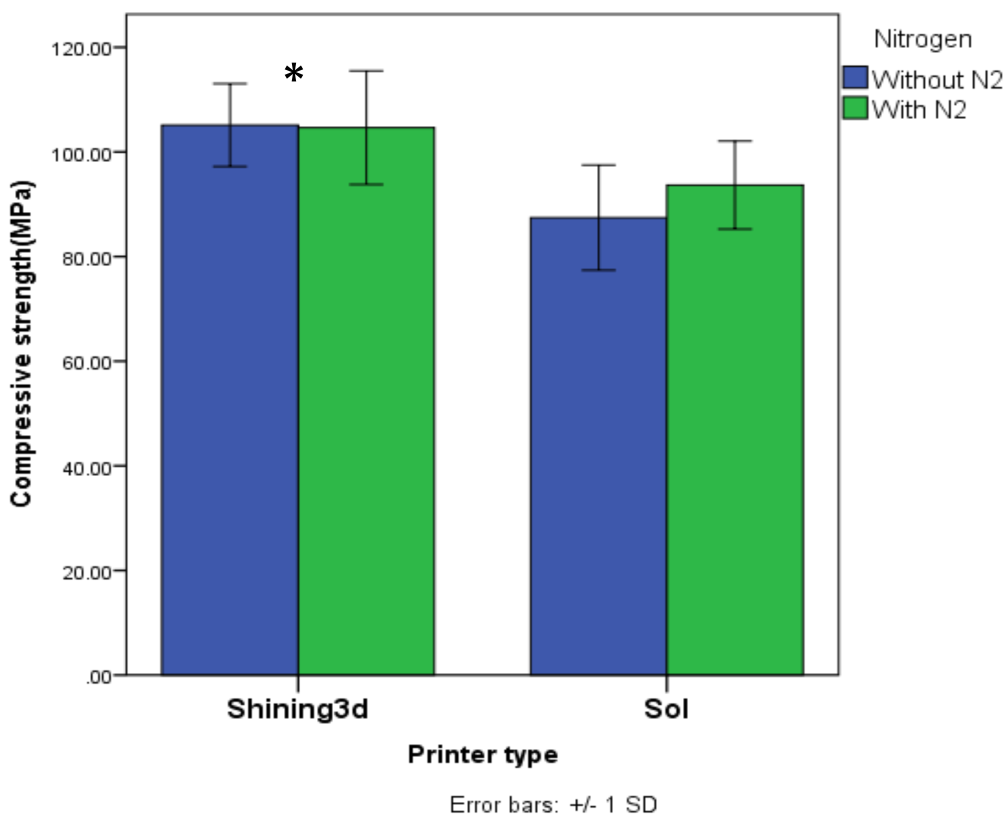

Figure 1. Clustered bar chart displaying the mean compressive strength (MPa) of the 3D-printed resin based on printer type and curing environment. Error bars represent +/- 1 standard deviation.

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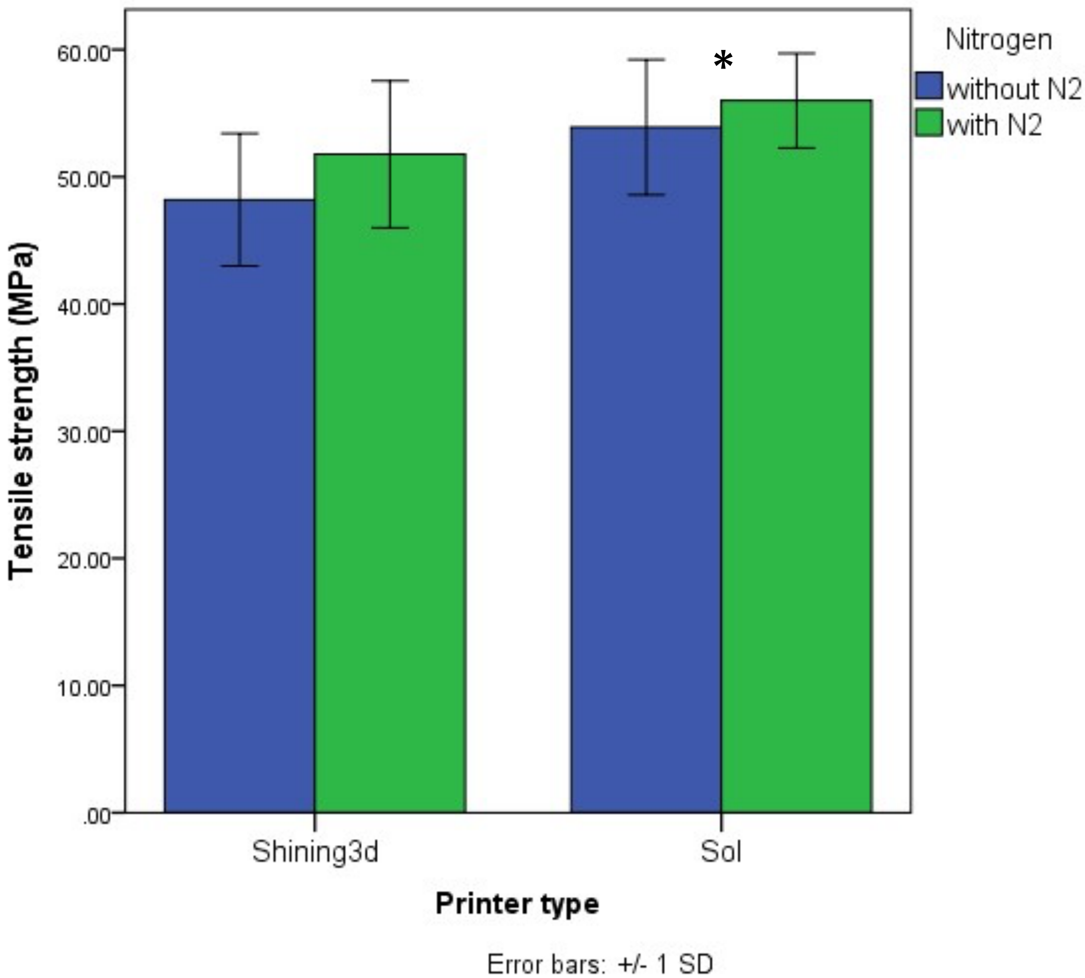

Figure 2. Clustered bar chart displaying the mean tensile strength (MPa) of the 3D-printed resin based on printer type and curing environment. Error bars represent +/- 1 standard deviation.

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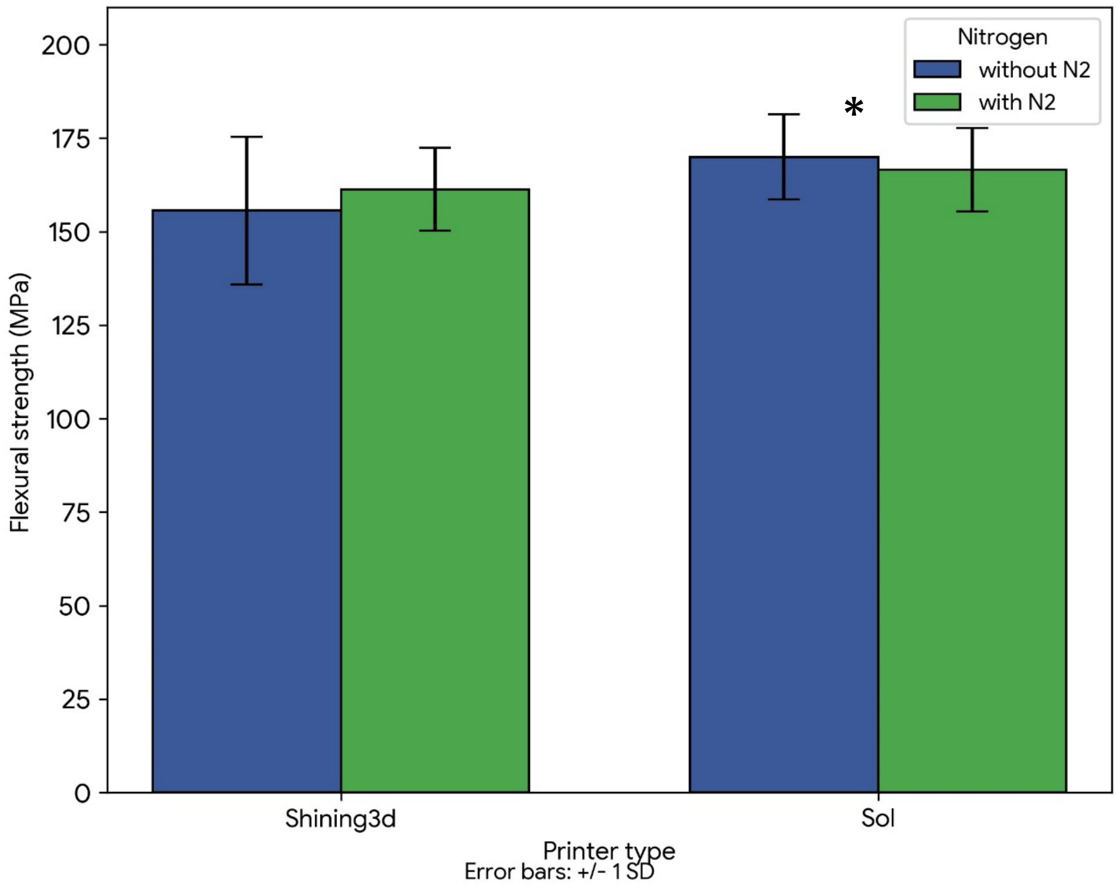

Figure 3. Clustered bar chart displaying the mean flexural strength (MPa) of the 3D-printed resin based on printer type and curing environment. Error bars represent +/- 1 standard deviation.