

Article

The Effect of Extrinsic Staining on 3D Printed Provisional Crowns

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Abstract: Purpose: The aim of this study was to evaluate the color stability of 3D printed resin disks using spectral reflectance data obtained at different time periods after immersion in various staining solutions. The color stability of 3D-printed temporary crowns is clinically important, as it directly affects the esthetic outcome and patient satisfaction during the provisional phase of treatment. Materials and methods: Forty identical round disk specimens measuring 10 mm in diameter and 2 mm in thickness were fabricated using CAD/CAM 3D printing resin (shade B1). Half of the specimens ($n = 20$) were polished using an acrylic bur and medium pumice. The remaining specimens were unpolished ($n = 20$). Each group of disks was then immersed in one of the following immersion solutions: artificial saliva, black tea, carrot juice, and red wine. Color difference ΔE was evaluated using the spectrophotometer, a spectral reflectance instrument, at baseline, day 1, week 1, week 2 and week 3, against a white background. Comparisons between polished and unpolished disks at each time point were conducted using Mann–Whitney tests. Differences among the staining solutions at each time point for both polished and unpolished disks were analyzed using a one-way ANOVA with Tukey’s post hoc test. Results: Color difference ΔE was measured using the CIELAB formula. The mean ΔE values of each group were calculated. The greatest difference in color was observed in the unpolished and polished disks immersed in red wine. Polished disks showed less color difference when compared to unpolished disks. Significant differences in ΔE were detected between polished and unpolished disks immersed in red wine at week 1 ($p = 0.0159$), week 2 ($p = 0.0079$) and week 3 ($p = 0.0079$) and in carrot juice at week 3 ($p = 0.0317$). Conclusions: Immersion of 3D printed disks in different staining solutions caused detectable color difference in the tested materials, which was relative to the immersion duration and the staining solution used. The color of the 3D printed resins is influenced by the surface finishing, which may result in visually perceptible color differences. The color stability of 3D printed materials should be improved to provide long-term esthetics.

Keywords: color stability; staining; 3D printed resin; DLP printing; temporary printed crown; CAD/CAM temporary crown; color difference ΔE ; dentistry



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1. Introduction

Provisional crowns play a crucial role in preserving the integrity of the remaining tooth structure following various dental procedures, such as crown preparations [1]. The use of provisional crowns ensures comfort, esthetics and appropriate masticatory function while allowing for the evaluation of the tooth prior to the placement of a permanent restoration [2,3].

In contemporary dentistry, patients have high esthetic expectations, thereby necessitating the development of materials and techniques that closely replicate the appearance of natural teeth. One of the factors that may influence the appearance, and therefore the esthetics, of interim prostheses, is the patient's dietary habits. This is especially important when diets incorporate beverages that possess a high potential for staining the surfaces they contact, such as wine, coffee, tea and soft drinks [4]. In fixed prosthodontics, several visits may be necessary to complete a treatment plan, and interim restorations are subjected to the patient's diet for long periods of time [5,6]. This need encourages the development of dental materials with improved color stability.

One of the commonly used interim materials in dentistry is polymethyl methacrylate (PMMA), developed in 1940 [7]. A study by Koppaka et al. subjected PMMA samples to coffee, tea, and red wine solutions for 30 days, simulating oral conditions, and the results indicated significant color changes, particularly with red wine, highlighting PMMA's susceptibility to staining from common beverages [8]. In addition to that, this material presents various disadvantages, including polymerization shrinkage, marginal inconsistencies and excessive heat created during polymerization [9]. The evolution of CAD/CAM technology, and the materials used with the digital workflow, has led to enhanced precision, accuracy, efficiency, clinical reliability and esthetics [10,11].

The manufacturing of temporary dental crowns through CAD/CAM techniques can be achieved using either additive or subtractive methods, each with distinct advantages and limitations [12,13]. Additive manufacturing, commonly known as 3D printing, involves layer-by-layer deposition of material to build the crown. This approach, as highlighted in articles by Joda et al. offers design flexibility, reduced material waste and the ability to create complex geometries [12]. Subtractive manufacturing methods, which involve milling the crown from a solid block of material, demonstrate high precision and excellent mechanical properties [13]. A study by Song et al. demonstrated that PMMA milling blocks showed relatively low color change up to 4 weeks but experienced a significant increase in discoloration after 8 weeks of immersion in coffee and tea solutions [14].

The color stability of 3D printed dental resin crowns has garnered attention due to their distinct material properties. Alharbi et al. demonstrates that 3D printed resin materials exhibit improved color stability over time [15]. The aim of this study was to evaluate the color stability of 3D printed resin, composed primarily of methacrylate monomers and diurethane dimethacrylate, when subjected to common staining solutions over time. Additive manufacturing was employed owing to its cost-efficiency and rapid fabrication process. The samples were divided into the following two groups: polished and unpolished. This approach aimed to assess the influence of surface finishing on color stability and consequently esthetics. The first null hypothesis was that there would be no significant difference in color stability among the samples immersed in the different solutions after 3 weeks. The second null hypothesis was that there would be no significant difference in color stability between the polished and unpolished samples after 3 weeks of immersion in the different solutions.

2. Materials and Methods

2.1. Designing and Printing

In the present investigation, the color stability of a printable resin immersed in various solutions was evaluated. Dentca Crown and Bridge (Dentca Inc., Torrance, CA, USA) shade B1 was selected. This resin is composed of a mixture that includes methacrylate monomer (40–60%), diurethane dimethacrylate (30–50%), trimethylolpropane trimethacrylate (3–10%), initiator (<3%), pigment (<0.7%) and a stabilizer (<1%). Resin disks were designed using CAD software Meshmixer (version 3.5.0, Autodesk, San Rafael, CA, USA) to the following specifications: 2 mm thick and 10 mm in diameter at a 45-degree printing angle. Supporting struts were automatically added through the software. A Standard Tessellation Language (STL) file was created, which contains the digital 3D model format. The file was sent to the RayWare software (version 2.8.X, SprintRay Inc., Los Angeles, CA, USA) which was used to prepare the print for the SprintRay Pro 95 S printer (SprintRay Inc., Los Angeles, CA, USA) (Figure 1). Instructions from the manufacturer were followed for the specific corresponding third-party resin used. The printer utilizes Digital Light Processing (DLP) optical technology. Its projector selectively emits light at an intensity of 23 mW/cm² to cure each layer of the image in 50-micron increments. The build platform was then removed and placed in a ProWash S (SprintRay Inc., Los Angeles, CA, USA) washing unit containing Isopropyl alcohol 91% for 10 min. All the disks were removed from the build platform using a spatula provided by SprintRay, and left in ProCure 2 (SprintRay Inc., Los Angeles, CA, USA) curing unit for 5 min. This machine uses a patented light motion drive UV LED system, emitting light at 385 nm wavelength.

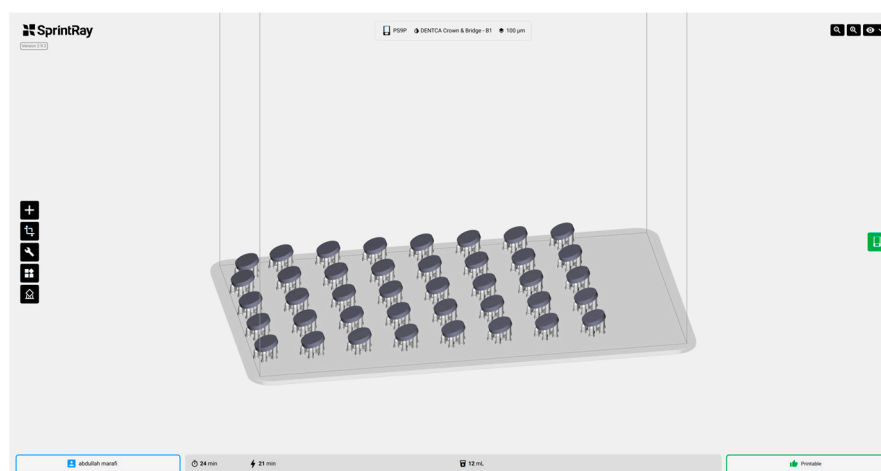


Figure 1. CAD design for disk specimens in SprintRay software.

2.2. Specimen Grouping and Solution Selection

After finalizing the post processing steps, the disks ($n = 40$) were divided into two equal groups. The sample size was determined based on previously published studies addressing similar topics [7,9]. One group was polished ($n_1 = 20$), while the other one remained unpolished ($n_2 = 20$). The fabrication of the unpolished disks was complete following post-process curing. Polishing of the remaining disks was carried out using a 3-step polishing kit (Acrylic Polisher Adjustment Kit 4543, Komet Dental, Fort Mill, SC, USA). The specimens were first polished with a coarse acrylic bur, then with a medium acrylic bur, and finished with a fine acrylic bur at an optimal speed of 6000 rpm. A dental lathe machine (Baldor 340 Dental lathe, Baldor, OH, USA) was used to pumice the same set of specimens at a slow speed setting with medium-grit pumice (Pumice Medium, Miltex Inc., York, PA, USA) that was mixed with tap water to the recommended consistency. Each

individual disk was polished using pumice and a wheel buff (2S, Felt Wheel Buff, Buffalo Dental Manufacturing Co., Inc., Syosset, NY, USA) for 20 s each.

For each disk, a one-ounce medicine cup was numbered according to the immersion solution. Each medicine cup was filled with half an ounce of one of the immersion solutions: artificial saliva (AS) (Biochemazone, Chemazone Inc., Leduc, AB, Canada), carrot juice (C) (Bolthousa Farms, Bakerfield, CA, USA), red wine (RW) (Cabernet Sauvignon, Bota Box Vineyards, Mentanaca, CA, USA), or black tea (BT) (Pure Leaf Iced Tea, PepsiCo, Purchase, NY, USA) (Table 1). Specimens were randomized to 4 groups according to the storage solution.

Table 1. Staining solutions used for disk immersion.

Staining Solution	Manufacturer
Artificial Saliva	Artificial Saliva, Biochemazone, Chemazone INC, Canada
Carrot Juice	Bolthouse Farms, Bakersfield, California
Red Wine	Cabernet Sauvignon, Bota Box Vineyards, Mentaca, California
Black Tea	Pure Leaf Iced Tea, PepsiCo, Purchase, New York

Color stability was assessed using the CIELAB ($L^*a^*b^*$) color space [9]. The color space was created by the Commission Internationale de l'Eclairage (CIE) in 1976 and describes differences in color perception based on human vision [16]. Coordinates in the color space that correspond to the lightness of the color (L^*) range from 0 (black) to 100 (white). The a^* axis represents the two colors green as (−) values and magenta as (+) values. On the intersecting axis, b^* represents blue with (−) values and yellow as (+) values [16]. The color difference, ΔE_{ab}^* between two colors is evaluated using the Euclidean distance equation between the coordinates of each color in space [17]:

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

ΔE_{ab}^* represents color difference in units. The difference may be perceptible or non-perceptible. Based on recommendations from the International Organization for Standardization article on guidance in color measurements in dentistry (ISO/TR 28642) [18], it was suggested that the CIELAB perceptibility threshold (PT) be at $\Delta E_{ab}^* = 1.2$, and the acceptability threshold (AT) at $\Delta E_{ab}^* = 2.7$. A ΔE_{ab}^* of 3.3 or above is clinically unacceptable [18,19].

2.3. Data Collection

Color values were measured using a digital spectrophotometer Easyshade (Vita Easyshade V, VITA, Bad Sackingen, Germany) at five distinct time intervals: baseline, day 1, week 1, week 2 and week 3 [9]. The spectrophotometer was calibrated according to the manufacture's recommendations. Readings were taken against a uniform white background. The control color values were taken at baseline before immersion of the disks in the solutions. The solutions were replaced weekly and stored at room temperature. Before each measurement, the disks were removed from the solutions and rinsed under tap water for 10 s to remove any excess solution and then dried using a 2 × 2 gauze. Following the Commission Internationale d'Eclairage (CIE) $L^*a^*b^*$ system, values for L^* , a^* and b^* were recorded. The ΔE_{ab}^* values for disks in each staining solution was calculated in Microsoft Excel using the Euclidean equation [9].

2.4. Statistical Analysis

Comparisons between polished and unpolished disks at each time point were made using Mann–Whitney tests. The Shapiro–Wilk test was performed to evaluate the normality of the data distribution. Comparisons among staining solutions at each time point for both polished and unpolished disks were made using a one-way ANOVA with Tukey’s post hoc test. Statistical significance was set to $p < 0.05$ for all tests. All statistical analyses and visualizations were performed in GraphPad Prism for MacOS (Version 10.0.3, GraphPad Software, Boston, MA, USA).

3. Results

Figure 2 presents visual color differences in the 3D printed resin disk after 3 weeks of immersion in the different solutions. Significant differences in ΔE were detected between polished and unpolished disks immersed in red wine at week 1 ($p = 0.0159$), week 2 ($p = 0.0079$), week 3 ($p = 0.0079$) and in carrot juice at week 3 ($p = 0.0317$) (Table 2). At day 1, unpolished disks immersed in red wine showed the greatest mean color difference; $\Delta E = 5.8$. Similarly, after week 1, unpolished disks showed an average of $\Delta E = 15.7$ compared to $\Delta E = 9.8$ for polished disks. The ΔE values exhibited a notable increase for the duration of the study, indicating a significant shift in color change within the tested samples (Figures 3 and 4). The increase was mainly prominent in red wine and carrot juice samples. Artificial saliva and black tea showed the least color difference. Significant differences ($p < 0.05$) among staining solutions were found in mean ΔE at each time interval for both polished and unpolished disks except for the unpolished disks at day 1. Tukey’s multiple comparisons test indicated significant differences ($p < 0.05$) in the mean ΔE between disks in red wine and each of the other solutions. No significant differences were observed between artificial saliva and carrot juice, carrot juice and black tea, or black tea and artificial saliva at any time point (Table 3).

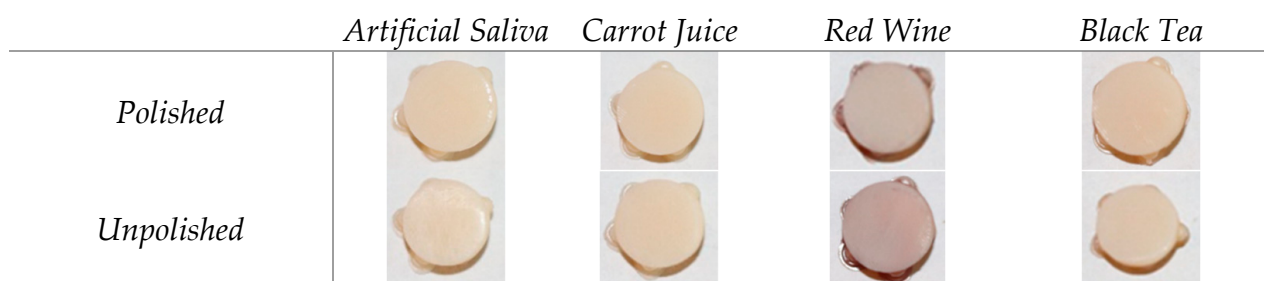


Figure 2. Visual representation of resin disks after 3 weeks in their corresponding solutions.

Table 2. Mean color difference in polished (P) vs. unpolished (UP) disks.

Solution	MEAN ΔE (SD)							
	Day 1		Week 1		Week 2		Week 3	
	P	UP	P	UP	P	UP	P	UP
Artificial Saliva	1.65 (0.52)	2.32 (0.86)	2.34 (1.04)	2.39 (1.40)	2.09 (0.59)	2.98 (1.84)	2.47 (1.82)	3.65 (1.63)
Carrot Juice	2.52 (0.91)	5.20 (2.77)	2.48 (0.96)	4.56 (3.28)	2.35 (0.62)	3.28 (2.92)	2.02 (0.49) *	7.10 (5.18) *
Red Wine	3.63 (1.27)	5.80 (2.03)	9.82 (2.20) *	15.77 (1.88) *	10.56 (1.89) *	18.97 (1.52) *	10.56 (1.82) *	19.94 (3.75) *
Black Tea	1.60 (0.60)	3.16 (1.79)	2.60 (1.08)	2.35 (0.76)	2.57 (0.34)	2.31 (0.65)	3.26 (0.66)	3.60 (0.86)

Note. SD = standard deviation; (*) represents significant difference: $p < 0.05$.

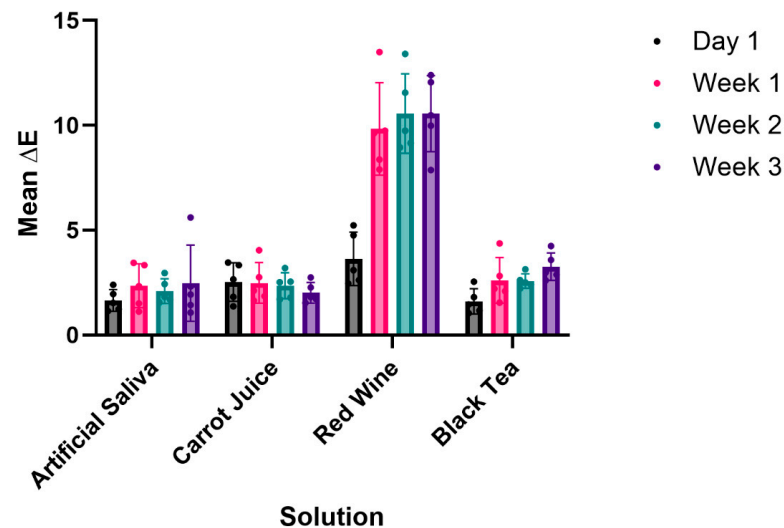


Figure 3. Mean color difference in polished disks.

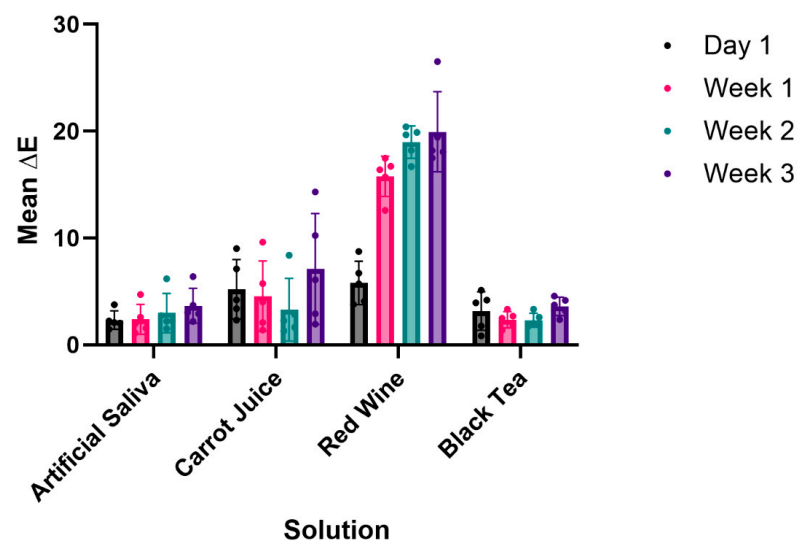


Figure 4. Mean color difference in unpolished disks.

Table 3. Results of one-way ANOVA and Tukey's test after day 1, week 1, week 2 and week 3 of immersion period.

Tukey's Test, Unpolished Red Wine vs:				
	ANOVA	Artificial Saliva	Carrot Juice	Black Tea
Day 1	0.0421	0.0593 (NS)	0.9623 (NS)	0.9623 (NS)
Week 1	<0.0001	<0.0001	<0.0001	<0.0001
Week 2	<0.0001	<0.0001	<0.0001	<0.0001
Week 3	<0.0001	<0.0001	<0.0001	<0.0001
Tukey's Test, Polished Red Wine vs:				
	ANOVA	Artificial Saliva	Carrot Juice	Black Tea
Day 1	0.0068	0.0126	0.2331 (NS)	0.0106
Week 1	<0.0001	<0.0001	<0.0001	<0.0001
Week 2	<0.0001	<0.0001	<0.0001	<0.0001
Week 3	<0.0001	<0.0001	<0.0001	<0.0001

Note. NS = non-significant difference.

4. Discussion

The purpose of this investigation was to evaluate the color difference among 3D printed resin disks immersed in four different staining solutions: artificial saliva, red wine, carrot juice and black tea. The solutions were chosen due to their prevalence in common diets. A spectrophotometer was used to determine the color coordinates of each printed disk. The VITA Easyshade V contains a spectrometer that captures reflected light. The reflected light contains information about the surface tested. Studies have shown that the reliability and accuracy of the device in shade detecting are 96.4% and 92.6%, respectively [19]. The CIELAB color space (L^* , a^* , and b^*) was used to calculate color difference, ΔE^*_{ab} , across time for both polished and unpolished resins stored in each staining solution. The study indicated that red wine affected the disk's color in week 1, week 2 and week 3, regardless of polishing state. Unpolished disks were less color stable in red wine compared to polished disks at week 1, week 2, and week 3. Moreover, surface treatment also showed differences in mean values for carrot juice at week 3. ΔE values for specimens immersed in artificial saliva and black tea did not exceed the value of 3.6, while carrot juice reached a maximum ΔE of 7.1 for unpolished disks. The highest mean value for unpolished disks immersed in red wine reached a ΔE of 19.94 (3.75).

The first null hypothesis was rejected, as a significant difference $p < 0.05$ was observed among the different solutions after three weeks of immersion. Red wine exhibited the highest color difference. This finding is consistent with the results of the study by Gruber et al., in which 176 tooth-colored and pink resin specimens were tested. These specimens were either conventionally heat polymerized PMMA resin, subtractively manufactured from a CAD/CAM block, or additively manufactured through 3D printing. Four aging processes were used in this study: thermal cycling, red wine, distilled water, and coffee. The results showed that the red wine group exhibited a greater tendency toward staining across all resin groups compared to the other aging processes [20].

The second null hypothesis was also rejected, as a significant difference $p < 0.05$ was found between polished and unpolished disks after three weeks of immersion in different staining media. This result aligns with the findings of the study by Raszewski et al., who evaluated the color stability of 3D printed resin with two different surface-finishing processes. Specimens were either polished using a 100-micron pumice or varnished with a light polymerized agent. Based on the results of this study, the greatest changes were observed for samples that were not polished and were placed in red wine dilutions. Regarding the samples covered with varnish, during storage, some parts detached, and the dyes penetrated inside [21].

When CAD/CAM PMMA blocks were compared to 3D printed resin, multiple studies concluded that CAD/CAM PMMA blocks were more color stable when immersed in colorant solutions [20–23]. Gruber et al., after calculating the ΔE results, showed higher color stability for both conventional heat-polymerized resin and subtractively manufactured resin samples when compared to 3D printed resin. Their study also showed that CAD/CAM subtractive manufactured resins and conventionally fabricated resin showed similar physical properties [20]. In the study by Shin et al., a colorimeter was used to measure color difference between three types of CAD/CAM blocks and two 3D printing resins. The results showed higher color stability in CAD/CAM block materials, with 3D printed resin showing perceptible color changes above their set clinic limit of 2.25 as early as 7 days [17]. When considering the acceptability and perceptibility tolerances of shade mismatch, a study by Douglas et al. was conducted in a clinical scenario. Twenty-eight dentists were questioned on the mismatch of two central incisors that ranged from $\Delta E = 1$ to $\Delta E = 10$. At a ΔE value of 2.6, 50% of the dentists could perceive a color difference. On the other hand, a failing restoration due to a mismatch of shade was set at $\Delta E = 5.5$ which

was detectable by half of the dentists [24]. In this study, values above 5.5 were only seen for red wine groups at day 1, week 1, week 2, and week 3, and for carrot juice specimens at week 3.

Multiple factors can affect the color stability of a 3D printed resin. Different studies have shown that the orientation on the build platform can affect both mechanical and optical properties. According to a study by Hada et al., a printing orientation of 45 degrees demonstrated the highest level of accuracy [25]. In another study by Espinar et al., selection between 0 and 90 degrees was evaluated to test if the printing orientation affects the translucency and color stability of 3D printing resin. Findings showed that building orientation can influence the translucency and color stability of the resin. Printing at a 90° angle showed higher translucency for some brands used. Choosing a printing orientation should be assessed individually for each resin depending on its composition and how layering the resin affects its absorption and scattering values [26]. Lee et al. investigated color stability of 3D printed resin under different printing parameters. One hundred and eighty disks, 15 mm in diameter and 2 mm in thickness, were printed and immersed in different solutions. Three printing orientations, 0°, 45° and 90°, and two thicknesses, 25 µm and 100 µm, were investigated at 1, 3, 7, 15, and 30 days after immersion. The resin samples in the 0° group had more color stability than those in the 45° and 90° groups, with the same layer thicknesses at the same time point. Under the same circumstances, the 100 µm resin samples presented significantly more color stability than the 25 µm samples [27].

Moreover, water sorption of resin material could have an impact on color stability. In the study by Shin et al., it was also observed that water sorption of 3D printed resin is higher than that of polycarbonate, but lower than that of prefabricated PMMA material [17]. Gad et al. similarly examined three 3D printed denture base resins and heat polymerized acrylic denture base resins. The effects of thermal cycling showed higher sorption rates among the 3D printed resin compared to the heat polymerized acrylic resin [28]. Although they are not the only causes, water sorption and solubility of the printed resin can influence the color stability of 3D printed resin materials.

Different 3D printing approaches can be used to fabricate restorations; in this study, a DLP printer was utilized. DLP 3D printers cure all points simultaneously by flashing an image of a layer across the entire platform via a digital projector screen. A stereolithography apparatus (SLA) is also a common type of 3D printer which uses a laser beam that reflects on the resin tank, curing point by point. The illumination source differentiates the two types of printers [29]. Limited studies comparing means of printing have been discussed in the literature. One study by Kim et al. evaluated color stability along with the physical and mechanical properties of resins fabricated using the following methods: manual, FDM, two polyjets, SLS, SLA, DLP, and milling. After 30 days of immersion, the milling method showed the highest color stability, with DLP, SLA and manual presenting similarly higher ΔE values [30].

Limitations of the Study and Future Direction

While the primary goal of this study was to evaluate the color stability of 3D printed resin and the effect of polishing on its color stability, it is essential to acknowledge the limitations that may affect the interpretation of the findings. This study only utilized DLP 3D printing technology. Stereolithography (SLA) is typically considered to be more color stable and to exhibit less surface roughness compared to DLP, due to the precise control of the curing process using a single consistent light source [31]. However, both technologies can achieve clinically acceptable color stability when properly calibrated and maintained [26]. Further research is warranted to compare the color stability of SLA versus DLP printed prototypes. In addition to that, future studies could focus on assessing fatigue

resistance, surface topography and bacterial adhesion to determine whether one of the two printing methods offers superior performance [6,32,33]. Another limitation is that only one type of 3D printing resin was tested for its color stability. Comparing more than one type of resin would ultimately show how inorganic fillers, matrices and photo initiators affect color stability. Lastly, the resin disks in this study were stored in solutions at room temperature, in closed containers. However, intraorally, these conditions differ. The temperature and pH fluctuate, and there is also the presence of saliva, which could potentially affect the accumulation of stains on the surfaces [34]. Future studies could be performed in vivo or in environments that simulate oral conditions to gain a better understanding of the material's performance within the oral cavity.

5. Conclusions

Unpolished provisional resin disks fabricated by DLP 3D printing showed lower color stability over time when compared to polished resin disks. Immersion in different staining solutions caused detectable color differences in the tested materials, relative to the immersion duration and the staining solution used. The color of the 3D printing restorative resins is influenced by the surface finishing, which may result in visually perceptible color differences. Three-dimensional printed material should be polished as thoroughly as possible to limit the adhesion of dyes from food to their surface. When selecting a material, the provider should take into consideration the longevity and esthetic demands of the treatment. The color stability of 3D printing materials should be improved to manufacture oral appliances that maintain long-term esthetic properties.

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