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Effects of Repolishing Systems on Surface Characteristics of a 3D-Printed Permanent Material

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Featured Application: The aesthetic stability of dental resin composites is an issue. Clinicians should know that this problem also affects 3D-printed permanent resin and that repolishing systems cannot completely recover the staining color shifts.

Abstract: Background: 3D-printed (3DP) resins for permanent restorations are increasing in availability and gaining popularity. Aesthetic stability is an issue of dental resins that may compromise the long-term success of restorations. A staining test has been performed to evaluate gloss, roughness, and color staining of a permanent 3DP resin, and the effects of repolishing. Methods: Squared specimens of one 3DP permanent resin (Crown permanent, Formlabs) have been CAD-designed and 3D-printed. After the roughness, gloss, and color measurements, they were immersed in a coffee staining bath at 44 °C for 24 h and then measured again. Subsequently, they were repolished with three different systems: prophy cup and Nupro prophy paste, HiLuster Plus 2-step, and Opti1Step Polisher 1-step polishing systems. Results: Gloss and Roughness were not significantly affected by the staining procedure. No significant changes were observed for gloss after repolishing, while one of the tested systems (prophy cup and paste) produced a worsening effect on roughness. Color was affected by the staining procedure. After repolishing, b* changes were almost completely recovered, while L* changes were recovered only partially. Conclusions: Color stability still represents a challenge, and 3DP resins for permanent use are affected. Repolishing systems should be further developed and tested.

Keywords: 3D printing; resin composites; staining; gloss; roughness; color stability

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1. Introduction

Aesthetics is one of the main objectives of restorative dentistry, which aims to restore the original natural appearance of sound teeth. If the tooth cannot be fully restored according to conservative principles, such as discoloration that is not resolvable with minimally invasive procedures or excessive loss of anatomical references, prosthetic treatment will be necessary [1,2].

Prosthetic restorations have undergone advancements to optimize aesthetic appeal and functional efficacy. These developments involve the integration of novel methodologies and innovative materials, enhancing the efficiency of manufacturing processes. Currently, the most commonly used materials for achieving excellent results are ceramics, like feldspathic, lithium disilicate, and zirconia [3–7].

Among the other materials used in aesthetic restorations, resin-based composite resins (RBC) play a fundamental role. They already provide excellent results in direct restorations and show sufficient longevity [8], even if one of their most discussed problems is color stability.

From a manufacturing point of view, the enhancements in CAD/CAM workflow allow the creation of indirect restorations through subtractive procedures (e.g., milling) in a clinically satisfactory and reproducible outcome associated with the use of ceramic-based materials such as feldspathic ceramics, lithium disilicate, zirconia, hybrid, and resin-based materials.

The 3D Printing manufacturing process has recently been introduced in the dental field [9,10]. Unlike the CAD/CAM technique, 3D printing is an additive process for creating prosthetic devices, performed by layering materials, with resin material already widely diffused and ceramic still in its beginning. This results in aesthetically improved indirect resin restorations and reduced material waste, thus increasing environmental sustainability [11] and reducing production timing and cost [12,13]. The primary challenge associated with this technique is its recent implementation, resulting in a still limited number of studies available. At first, 3D printing in prosthetic dentistry was suitable only for temporary materials, as there were many conflicting aspects, especially about the mechanical properties, dimensional accuracy, and fit of the 3D-printed materials. More recently, permanent resin materials have been marketed [11,14–16]

Exposure of traditional direct and indirect resin-based materials to different staining substances, such as coffee, red wine, chlorhexidine mouthrinses [17,18], and smoke [19], has been extensively evaluated in the scientific literature, giving a reasonably clear indication of the alterations in the resin's chromatic properties. For example, different formulations and uses of resins induce different results, and CAD/CAM resin-based materials show better chromatic stability than direct and indirect resin-based composites (RBCs) [20]. For the 3DP resins, most of the information is still missing or scarcely addressed. Likewise, repolishing procedures may allow reverting color change below the clinical acceptability threshold in specific clinical situations, avoiding the immediate need to replace stained restorations [21]. For this aspect as well, little information is available about 3D-printed resins.

This study evaluated coffee's ability to stain and/or alter the surface characteristics (gloss and roughness) of a 3D-printed resin for permanent restorations. Additionally, three different repolishing systems were assessed for their ability to restore color and surface properties of the 3D-printed resin material tested. The null hypothesis tested was that neither exposure of the device to a coffee-based staining solution nor different repolishing techniques significantly affected the material's color, gloss, and roughness.

2. Materials and Methods

One resin (Permanent Crown Resin, Formlabs, Somerville, MA, USA) for 3D-printing permanent prosthetic restorations was tested. Table 1 provides comprehensive details regarding the material analyzed in this study.

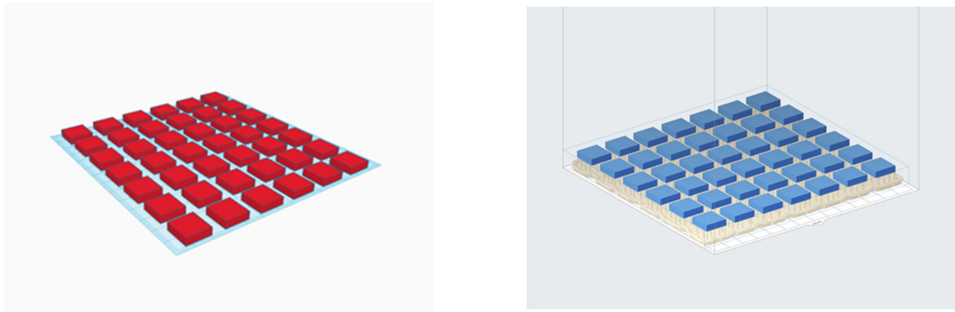
Table 1. Composition of the tested 3D-printed resin-based composite.

Chemical Component	Weight Percentage
Bis-EMA [1]	≥50–<75
Silanized glass	30–50

[1] Bis-EMA (bisphenol A diglycidyl methacrylate ethoxylated).

2.1. Specimen Preparation

Samples (14 mm × 14 mm × 4 mm) were designed using Thinkercad software (Autodesk, San Rafael, CA, USA) (Figure 1). The design was exported in .stl format and subsequently imported into the PreForm software (The software version numeber is 3.32.0, Formlabs, Somerville, MA, USA) for automated support generation and slicing.



(**a**) (**b**)

Figure 1. Specimens designed by Thinkercad software (**a**) and automatic support calculation and slicing performed by PreForm program (**b**).

The print settings were set to 50 μ, and the exposure time matched the software's recommendations for the tested resin. The specimens were 3D-printed using the Formlabs 3B printer (Formlabs, Somerville, MA, USA). After the printing process, the specimens were removed from the printing platform and underwent a 3 min cleansing using the FormWash (Formlabs, Somerville, MA, USA), an automatic washing machine from the same printer's manufacturer, following the operational guidelines. These required 99% isopropyl alcohol (IPA) to remove any residual unpolymerized resin. Following the washing process, the specimens were cured for 20 min at 60 °C in an automated polymerization device again from the same manufacturer of the printer and of the resin tested (FormCure, Formlabs, Somerville, MA, USA).

Following manufacturer instructions, the specimens were sandblasted with 50 glass beads (Perlablast micro, Bego, Bremen, Germany) at 1.5 bar to remove residual resin filler from the sample surface. Subsequently, an additional polymerization cycle was carried out in the FormCure for 20 min at 60 °C (Figure 2).

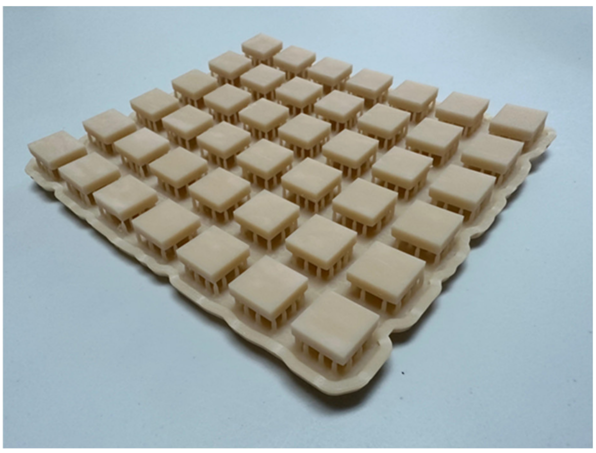


Figure 2. Permanent Crown Resin printed specimens.

The samples were then marked on one edge to identify the surface and orientation for subsequent polishing and repolishing procedures. The specimens were removed from the supports and manually polished using composite polishing burs. In particular, Vita

ENAMIC Polishing Set and diamond paste preloaded disc were employed: the pink bur was used for pre-polishing (8500 rpm), the gray one for high-gloss polishing (6500 rpm), and finally the Dia-Finish L 40-0001 (Renfert, Hilzingen, Germany) at 4500 rpm.

The burs were employed according to the manufacturer's guidelines without water cooling. According to the repolishing procedure, thirty specimens were randomly divided into three groups (n = 10).

2.2. Color Measurements

Color coordinates L*, a*, b* of the CIELAB color system were measured using a colorimeter with diffuse light and a d/8° viewing geometry (Color Meter Pro, CHNSpec, Hangzhou, China) on a 50% gray background, featuring an 8 mm opening integrating sphere, and a proprietary measurement software (Color Meter 2.2.24). At the beginning and after each group measurement, calibration was performed as indicated by the manufacturer. The D65 illuminant and a 10° standard observer were selected. Three readings were performed for each specimen, and the average values of color coordinates were obtained. The color measurements were performed at baseline (T0), after staining procedure (T1), and after repolishing procedures (T2).

2.3. Roughness Measurement

The roughness (Ra) was measured with a contact profilometer (Mitutoyo SJ-201P, Mitutoyo, Kanagawa, Japan), set with a cutoff value of 0.8 mm, a stylus speed of 0.5 mm/s, and a tracking length of 5.0 mm [22]. As Ra values may vary depending on the measurement position, standardization of measurements was achieved by using a CAD-designed and 3D-printed proprietary support mold that secured both the sample and the measurement probe in a fixed and reproducible position. Ra values were measured at baseline (T0), after the staining procedure (T1), and after the repolishing procedure (T2).

2.4. Gloss Measurement

The gloss assessment was performed through a compact aperture glossmeter (JND-XA6-SA; VTSYIQI Lab Measuring Instruments, Hafei, China), with a reading area of 2 mm × 2 mm, and a reading angle of 60°, following ISO 2813 specifications [23]. Measurement standardization was ensured through one support securing both the specimen and the measuring device in a steady and reproducible position. Gloss Unit (GU) data were recorded at baseline (T0), after the staining procedure (T1), and after repolishing procedures (T2).

2.5. Staining

A total of 6 g of coffee powder (Nescafé Gold, Nestlé Italia, Assago, Italy) were diluted in 0.5 l of boiling distilled water. After 10 min of stirring, the coffee solution was filtered using filter paper. The staining solution was kept at 44 °C ± 1 °C. The samples were submerged in the coffee solution for 24 h. The staining solution was renewed every 6 h [17,20].

After removal from the staining solution, the specimens were ultrasonically cleaned in a 95% ethanol solution for 3 min and then dried using an oil-free air jet (Figure 3). Subsequently, the samples were re-measured according to the procedure above (T1).

2.6. Repolishing

After staining procedures, the specimens were repolished using the following methods:

Group 1: Dental prophylaxis cups (Dental Trey, Fiumana–Predappio, FC, Italy) 7 mm palm-shaped, 10,000 rpm with water cooling, and Nupro prophylaxis paste with 'coarse' granularity (Dentsply Sirona, Charlotte, NC, USA);

Group 2: two-step HiLuster Plus Polishing System (Kerr, Orange, CA, USA) at 10,000 rpm; Group 3: One-step Opti1Step Polisher System (Kerr, Orange, CA, USA) at 10,000 rpm.

After repolishing, the specimens were re-measured according to the procedure above (T2).

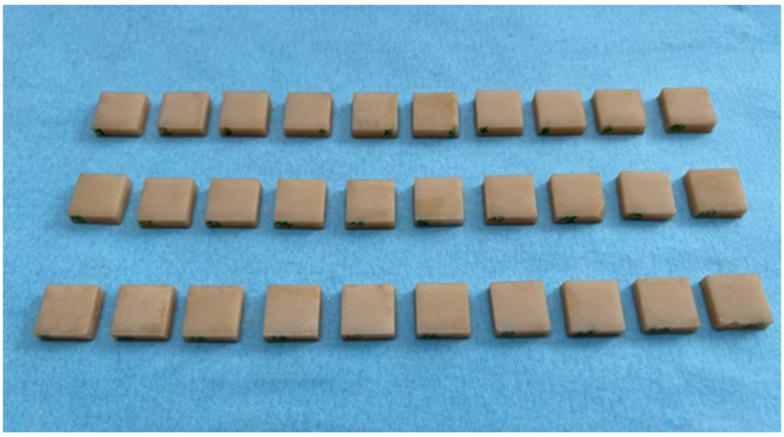


Figure 3. The samples at the end of the staining procedure.

2.7. Statistical Analysis

The Shapiro–Wilk and Levene tests were applied to verify that the collected data met the normality of data distribution and homogeneity of group variances, respectively. For each dependent variable (L*, a*, b*, roughness, gloss), a Two-Way Repeated Measures Analysis of Variance (ANOVA) was performed with measurement time as the within-subjects factor and the experimental group as the between-subjects factor. The statistical significance of the between-factor interaction was also assessed. The Tukey test was used for post hoc comparisons as needed. The significance level was set at $p < 0.05$ in all the tests.

3. Results

The descriptive statistics of the variables L*, a*, b*, roughness, and gloss at baseline (T0), after staining (T1), and after repolishing (T2) are reported in Tables 2–6, along with the outcome of the statistical analysis.

Table 2. Descriptive statistics and outcome of statistical analysis of L* data. Different superscript letters indicate statistically significant differences among measurements taken at subsequent time intervals.

Time Intervals	Group	Mean	Standard Deviation	n
T0	1	64.9	0.5	10
	2	65.1	0.3	10
	3	64.7	0.5	10
	T0 total ^{A}	64.9	0.4	30
T1	1	62.9	0.6	10
	2	62.9	0.8	10
	3	62.6	0.6	10
	T1 total ^{C}	62.8	0.7	30

Table 2. *Cont.*

Time Intervals	Group	Mean	Standard Deviation	n
T2	1	64.8	0.4	10
	2	64.4	0.5	10
	3	64.6	0.2	10
	T2 total ^{B}	64.6	0.4	30
Total group n = 30	1	64.2	1.1	10
	2	64.2	1.1	10
	3	64.0	1.1	10

Table 3. Descriptive statistics and outcome of the statistical analysis of a* data. Different superscript letters indicate statistically significant differences among measurements taken at subsequent time intervals.

Time Intervals	Group	Mean	Standard Deviation	n
T0	1	0.01	0.4	10
	2	−0.08	0.3	10
	3	0.2	0.4	10
	T0 total ^{A}	0.04	0.4	30
T1	1	0.2	0.3	10
	2	0.1	0.2	10
	3	0.3	0.3	10
	T1 total ^{B}	0.2	0.3	30
T2	1	−0.5	0.3	10
	2	−0.4	0.1	10
	3	−0.5	0.2	10
	T2 total ^{C}	−0.5	0.2	30
Total group n = 30	1	−0.1	0.5	10
	2	−0.1	0.3	10
	3	0.0	0.5	10

Table 4. Descriptive statistics and outcome of the statistical analysis of b* data. Different uppercase superscript letters highlight statistically significant differences among measurements taken at subsequent time intervals. Different lowercase upper script letters indicate statistically significant differences among measurements taken at subsequent time intervals within each experimental group (underlined for group 1, italic for group 2, bold for group 3). Different Greek alphabet letters in superscript labels statistically significant differences among experimental groups at T0.

Time Intervals	Group	Mean	Standard Deviation	n
T0	$1^{\underline{a}\,\alpha}$	9.8	0.3	10
	$2^{a\,\alpha}$	9.7	0.4	10
	$3^{\mathbf{a}\,\beta}$	11.4	0.2	10
	T0 total ^{A}	10.3	0.8	30

Table 4. *Cont.*

Time Intervals	Group	Mean	Standard Deviation	n
T1	1 [c]	13.7	1.2	10
	2 [c]	13.6	1.1	10
	3 [b]	13.6	1.1	10
	T1 total [C]	13.7	1.1	30
T2	1 [b]	10.6	1.3	10
	2 [b]	11.2	0.9	10
	3 [a]	10.7	0.9	10
	T2 total [B]	10.8	1.0	30
Total group n = 30	1	11.4	2.0	10
	2	11.6	1.9	10
	3	11.9	1.5	10

Table 5. Descriptive statistics of roughness data. Neither factor, nor the between-factor interaction was statistically significant.

Timing	Group	Mean	Standard Deviation	n
T0	1	0.51	0.24	10
	2	0.40	0.08	10
	3	0.55	0.31	10
	T0 Total	0.49	0.23	30
T1	1	0.51	0.24	10
	2	0.39	0.08	10
	3	0.54	0.23	10
	T1 Total	0.48	0.20	30
T2	1	0.51	0.12	10
	2	0.41	0.10	10
	3	0.45	0.14	10
	T2 Total	0.46	0.13	30
Total group n = 30	1	0.52	0.21	10
	2	0.41	0.09	10
	3	0.52	0.24	10

3.1. L Color Coordinate*

The Two-Way Repeated Measures ANOVA revealed that L* values recorded at subsequent experiment stages differed significantly ($p < 0.001$). Specifically, *L decreased after coffee staining. Repolishing inverted the change in the color parameter, though not restoring the initial condition. All these differences were statistically significant according to the post hoc test ($p < 0.05$). The repolishing technique did not emerge as a significant factor per se ($p = 0.48$). The between-factor interaction was also non-significant from a statistical point of view ($p = 0.27$) (Table 2).

Table 6. Descriptive statistics and outcome of the statistical analysis of gloss data (GU). Different uppercase letters in superscript identify statistically significant differences among groups. Different lowercase letters in superscript denote statistically significant differences among measurements within each experimental group (underlined for group 1, bold for group 3). Different Greek alphabet letters in superscript highlight statistically significant differences among the groups at T2.

Timing	**Group**	**Mean**	**Standard Deviation**	**n**
T0	1	$19.5^{\underline{a}}$	5.3	10
	2	21.4	4.8	10
	3	$18.9^{\mathbf{b}}$	4.8	10
	T0 total	19.9	4.9	30
T1	1	$19.8^{\underline{a}}$	4.5	10
	2	21.9	5.4	10
	3	$19.3^{\mathbf{b}}$	6.3	10
	T1 Total	20.3	5.4	30
T2	1	$9.2^{\underline{b}\beta}$	3.0	10
	2	26.5^{α}	8.6	10
	3	$28.4^{\mathbf{a}\ \alpha}$	9.1	10
	T2 Total	21.3	11.3	30
Total group n = 30	1^{B}	16.2	6.6	10
	2^{A}	23.3	6.7	10
	3^{A}	22.2	8.1	10

3.2. a Color Coordinate*

The Two-Way Repeated Measures ANOVA disclosed that the a* measurements recorded at succeeding stages of the experiment differed significantly ($p < 0.001$). In particular, a* increased with staining and shifted to negative with repolishing. These differences were statistically significant according to the post hoc test ($p < 0.05$). Neither the repolishing technique factor per se ($p = 0.59$), nor the between-factor interaction ($p = 0.24$) was found to be statistically significant (Table 3).

3.3. b Color Coordinate*

It emerged from the Two-Way Repeated Measures ANOVA that b* values differed significantly at subsequent stages of the experiment ($p < 0.001$). Similarly to a*, b* was lowered by immersion in coffee solution, and repolishing inverted the change, though not recovering the baseline characteristics. All these differences were statistically significant according to the post hoc test ($p < 0.05$). The repolishing technique was not a significant factor per se ($p = 0.29$). Nevertheless, the between-factor interaction was statistically significant ($p < 0.001$). Particularly, the post hoc test pointed out that 1-step repolishing (group 3) produced b* values statistically comparable to baseline ($p > 0.05$) (Table 4).

3.4. Roughness Measurements

The Two-Way Repeated Measures ANOVA revealed that surface roughness did not significantly change following immersion in the staining solution and subsequent repolishing (time factor significance $p = 0.45$; group factor significance $p = 0.27$). Also, the between-factor interaction was not statistically significant ($p = 0.36$) (Table 5).

3.5. Gloss Measurements

According to the Repeated Measures ANOVA, no statistically significant difference existed among the gloss values recorded at subsequent time intervals ($p = 0.59$). When assessing the effect of the polishing technique per se, statistically significant differences emerged among the groups ($p = 0.001$). Specifically, according to the post hoc test, specimens repolished with rubber cups and Nupro prophylactic paste (group 1) exhibited significantly lower gloss than the other specimens ($p < 0.05$). The between-factor interaction was found to be statistically significant ($p < 0.001$). Specifically, the post hoc test indicated that polishing with rubber cups and Nupro prophylactic paste (group 1) significantly reduced gloss ($p < 0.05$); conversely, 1-step polishing (group 3) enhanced gloss to a statistically significant extent ($p < 0.05$). At the end of the experiment (T2), specimens treated with rubber cups and Nupro prophylactic paste (group 1) exhibited the lowest gloss, and the difference was statistically significant according to the post hoc test (Table 6).

4. Discussion

The statistical analysis of the collected data led to the rejection of the formulated null hypothesis. The analysis revealed that exposure to the coffee solution induced significant alterations in the three color coordinates measured. It is worth noting that the three coordinates influence the perception of dental color differently. The L* coordinate (Lightness) denotes the amount of gray in a color. It is hence primarily accountable for the perception of dental color as either "darker" or "lighter", holding substantial importance in dental color perception. Conversely, the a* coordinate represents the quantity of green or red present in the color (positive values for red and negative values for green), with limited significance in the perception of dental color. The b* coordinate indicates the amount of blue and yellow within a color (positive values for yellow and negative for blue) and in dental color undergoes considerably more variation than the a* coordinate, representing the "yellowing" effect in dental color perception, thus playing a significant role.

The staining did not significantly affect the brightness or surface roughness, and the repolishing procedure had little influence on this property, regardless of the specific method employed.

Repolishing proved to be quite effective in restoring the three color parameters, even if complete restoration to the pre-discoloration values was achieved only for the b* variable and only following repolishing with the 1-step system (group 3). Remarkably, this procedure increased the initial Lightness levels. Conversely, brightness was notably decreased after repolishing with prophy cup and Nupro paste (group 1).

Roughness and gloss are clinically significant characteristics of materials used for dental restorations. Roughness can be described by various linear (Ra, Rq, Rz) or three-dimensional (Sa, Sq, Sz) parameters [24–26]. In this study, following previously published scientific literature [24], it was decided to measure Ra, which represents the average arithmetic value of all absolute distances from the surface profile within the measurement length. This is the most commonly used parameter to evaluate the impact of polishing techniques on restorative materials. Previous studies have demonstrated that the average Ra value of a restorative material should be below 0.2 µ [25] to minimize bacterial adhesion [27]. In the present investigation, all recorded Ra values exceeded the threshold above, being approximately 0.5 µ (Table 5). Nonetheless, it is noteworthy that intact human enamel typically exhibits Ra values ranging from 0.45 µ to 0.65 µ [27,28]. Consequently, it can be inferred that the 3D-printed resin for prosthetic restorations tested in the study exhibited surface roughness similar to that of natural enamel and maintained this characteristic even after the discoloration test.

Gloss is defined as the specular reflection from a surface and is determined according to ISO standards by comparing the intensity of incident light at a 60° angle with the intensity of light reflected from the surface at an equal angle but in the opposite direction. Its refractive index and surface morphology influence the material's gloss. Generally, the rougher the surface, the lower the gloss [24]. However, these two properties have different physical natures: the former being physical and the latter optical.

In contrast to surface roughness, a clinical acceptability threshold for gloss has not yet been established [27]. Nevertheless, in evaluating gloss, reference can be made to the data available in the literature regarding natural enamel, considering that the composite resins judged visually similar to human enamel have been reported to exhibit gloss values ranging between 40 and 47 GU [27,29], which is therefore considered the reference range for enamel. In this study, all gloss values measured for the tested resin (Table 6) are lower than those attributed to natural enamel. Nevertheless, it is essential to note that there is still ongoing disagreement in the literature regarding the optimal viewing geometry for gloss measurements. Furthermore, the lack of uniformity in experimental conditions across studies precludes direct comparison of the data obtained.

Only one paper reported the surface roughness and gloss of Permanent Crown Resin. Vichi et al., in a recent study [30], analyzed several different finishing and polishing methods and reported that all of the tested systems were able to achieve clinically acceptable results for roughness. In contrast, less acceptable results were obtained for gloss, except for a nitrogen chamber glazed system, which achieved excellent results for both roughness and gloss. A recent study focused on measuring the translucency of Permanent Crown Resin [31], and another analyzed its optical properties [32], although examining different parameters than the L*, a*, and b* color coordinates of the CIELAB system measured in the present study. When compared to prior studies conducted on materials for prosthetic crowns using the same measurement techniques and methods applied in this study, it is shown that Permanent Crown Resin exhibited a surface roughness exceeding that of CAD-CAM feldspathic ceramic Vita Mark II [27] and similar to that of lithium disilicate ceramics such as VITA Suprinity and IPS e.max CAD [24]. Conversely, its gloss was notably lower than that of both ceramic types. Moreover, the roughness and gloss of Permanent Crown Resin were found to be lower than those of bulk composite resins for direct restorations tested under similar experimental conditions [33].

When comparing the three polishing techniques used in this study, the Opti1Step Polisher yielded the most favorable results, supporting the manufacturer's assertions about its ability to achieve high gloss on composite resin surfaces in a single step. Conversely, the pumice particles in the Nupro prophylactic paste, designated as "coarse", may have exerted an abrasive impact on the material's surface, potentially diminishing its reflectivity. As a limitation of the study, even if representative of the procedures traditionally carried out during hygiene and repolishing, only three systems were used.

Another limitation of the present study is that, even if representative of a "*commonly used dental composite polishers*" reported in the IFU of the tested materials, only one system has been selected for the initial finishing and polishing procedure, which is essential as baseline. Different strategies for achieving an initial excellent finishing and polishing degree could be the object of further studies. Likewise, it could be of interest to consider the possibility of finishing this material with glazing rather than mechanical systems.

Further development of this study could involve examining how the material's printing orientation affects its optical characteristics, which appears to be a crucial factor in additive manufacturing. Additionally, other conditions in the oral cavity may influence the optical material properties, such as hydrolytic and UV aging and exposure to smoke.

These aspects deserve further investigation, especially concerning the improvement of the clinical environment simulation.

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