Effect of Polymerization Unit, Polishing, and Coffee Thermocycling on the Color and Translucency of Additively Manufactured Resins Used for Definitive Prostheses

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Purpose: To evaluate the effect of polymerization unit, polishing, and coffee thermocycling on the color and translucency of additively manufactured polyurethane-based resins with different viscosities. In addition, their color behavior was compared with the color of the shade tab throughout the fabrication steps and aging. ***Materials and Methods:*** Disk-shaped specimens (Ø10 × 2 mm) were fabricated from polyurethane-based resins with different viscosities (Tera Harz TC-80DP and C&B permanent; n = 30 per material). Baseline color coordinates were measured after cleaning. The specimens in each resin group were divided into three subgroups (n = 10 per subgroup) to be polymerized with different polymerization units (Otoflash G171 [FLN], Wash and Cure 2.0 [CLED1], and P Cure [CLED2]), polished, and subjected to coffee thermocycling. Color coordinates were remeasured after each process. Color differences (ΔE00) and relative translucency parameter (RTP) values were calculated. Data were statistically analyzed (α = .05). ***Results:*** Time points and polymerization units affected the ΔE00 for each material ($P \leq .049$). ΔE00 of each polymerization unit pair had significant differences within and among different time points within each material ($P \leq .024$). ΔE00 (when compared with the shade tab) and RTP were mostly affected by polymerization units and time points within both materials ($P \leq .042$). ***Conclusions:*** Tested polymerization units, polishing, and coffee thermocycling affected the color difference and translucency of tested resins. Color differences ranged from moderately unacceptable to extremely unacceptable, and the differences in translucency values mostly ranged from perceptible to unacceptable, according to previous thresholds. In addition, tested resin–polymerization unit pairs had unacceptable color differences when compared to the shade tab. CLED1 may enable higher color stability for tested resins. *Int J Prosthodont 2024;37(suppl):s19–s29. doi: 10.11607/ijp.7406*

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CAD/CAM technologies have enabled the use of additive manufacturing, which has started to increase in popularity given its advantages over subtractive manufacturing, such as lower fabrication cost, less waste, and the ability to manufacture objects with complex geometries.[1–5] In addition, a wide range of materials can be fabricated using additive manufacturing,[6] and recently introduced resins indicated for definitive prostheses are among them.[7,8] Currently available additively manufactured resins differ in chemical composition,[9] which also leads to differences in viscosities.[10] High polymerization shrinkage might be observed when the resin viscosity is too low, whereas agglomeration might be observed when the resin viscosity is too high.[11] Nevertheless, the resins printed via vat polymerization-based additive manufacturing technologies, such as digital light processing (DLP), are required to have low viscosity to ensure that the polymerized layer on the build platform is thoroughly coated with resin for a smooth surface that is polymerized completely without any voids.[10,12] A recent study concluded that resins with a viscosity > 1,500 centipoise (cP) will impair the fabrication process when using DLP printers.[13]

Postprocessing, which consists of the removal of excess resin and further polymerization, is an indispensable part of additive manufacturing,[14] particularly for resins indicated for definitive use. Polymerization ensures an adequate degree of conversion that will enhance the biocompatibility and the mechanical and optical properties of resins.[15–18] Resins are generally polymerized using the high amount of energy irradiated from polymerization units[16] that comprise different sources of energy, such as xenon lamps and light-emitting diodes (LEDs).[19] In addition, some of the polymerization units utilize nitrogen or a vacuum atmosphere to prevent the formation of an oxygen inhibition layer and improve polymerization efficiency.[16] However, some resin manufacturers recommend their own proprietary polymerization unit for postprocessing,[2,3] and clinicians and dental technicians might need to purchase additional units rather than using the ones already owned, which increases costs. Some clinicians and dental technicians may even use only one unit to polymerize all types of resins. Therefore, studies on the effect of various polymerization units on different resins may elaborate the applicability of these devices in clinical practice.

Previous studies on the effect of polymerization units have evaluated how the mechanical properties of denture bases,[15] occlusal devices,[3,19] provisional fixed prostheses,[20,21] surgical guides,[22] and resin composite materials[16] were affected. However, the knowledge on the effect of polymerization units on optical properties, particularly those of additively manufactured resins, is limited. There is only one study in the literature that has investigated how coffee thermocycling affected the optical properties of additively manufactured definitive resins.[23] However, Çakmak et al's[23] study did not involve the effect of polishing on optical properties. Therefore, the present study aimed to investigate how different polymerization units with varying costs, polishing, and coffee thermocycling affected the color and translucency of additively manufactured resins with different viscosities. In addition, the color of tested additively manufactured resins was compared to a shade tab for each polymerization unit–time point pair.

For the color analysis, the null hypotheses were: *(1)* there would be no difference in color difference (ΔE00) values among time points (after polymerization, after polishing, and after coffee thermocycling) within each material–polymerization unit pair; *(2)* there would be no difference in ΔE00 values among polymerization units within each material–time point pair; *(3)* there would be no difference in ΔE00 values among different time points within each polymerization unit pair for each material; and *(4)* there would be no difference in ΔE00 values among polymerization unit pairs within each material–time point pair. For the verification of color by comparison to a shade tab, the null hypotheses were: *(5)* there would be no difference in ΔE00 values among different time points within each material–polymerization unit pair when compared to shade tab; and *(6)* there would be no difference in ΔE00 values among polymerization units within each material–time point pair when compared to the shade tab. Lastly, in terms of relative translucency parameter (RTP) measurements, the null hypotheses were: *(7)* there would be no difference in RTP values among different time points within each material–polymerization unit pair; and *(8)* there would be no difference in RTP values among polymerization units within each material–time point pair.

MATERIALS AND METHODS

The methodology of the present study is summarized in Fig 1. A pilot study was performed prior to the present study to determine the number of specimens in each group, and the post hoc power analyses revealed 5 specimens to be adequate with 90% power, a minimum effect size of 0.75, and $\alpha = .05$. However, 10 specimens per group were fabricated to increase the statistical power and compensate for any loss during the procedures.

A disk-shaped specimen (Ø10×2-mm) was designed by using a software program (Meshmixer version 3.5.474, Autodesk) and imported into the proprietary nesting software program (Composer, Asiga) of a DLP-based 3D printer (MAX UV, Asiga). The specimen was positioned vertically toward the build platform,[24] and the support structures were generated automatically. This configuration was duplicated 10 times, and a total of 60 specimens were printed from a high-viscosity (HVR;

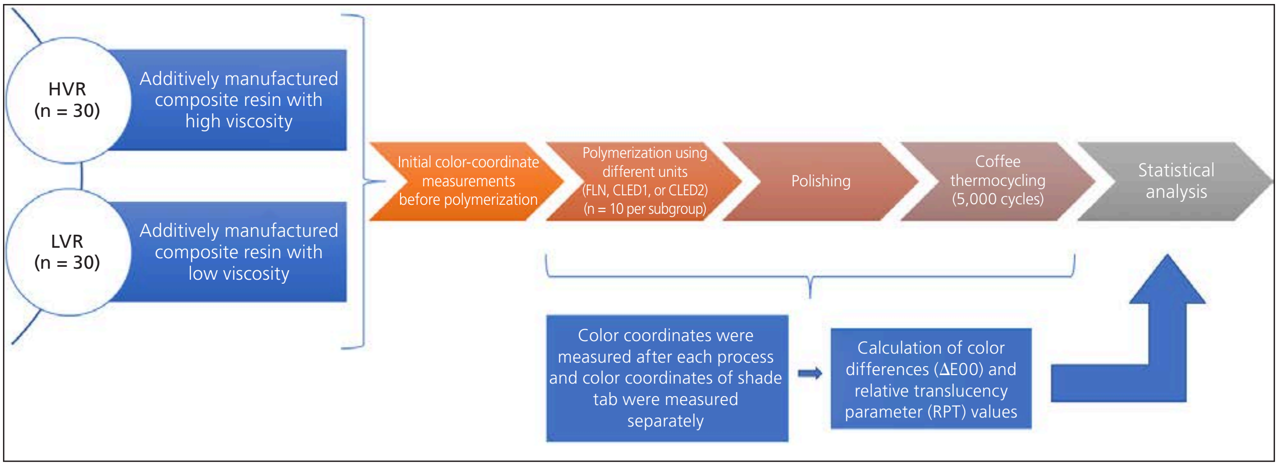

Fig 1 Flowchart of the study design.

Table 1 Materials Tested

Material	Chemical composition	Abbreviation	Viscosity
Tera Harz TC-80DP C&B (Graphy)	Urethane acrylate oligomer, bisphenol A ethoxylate dimethacrylate, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	HVR	3,525 cP
C&B Permanent (ODS)	Diurethane dimethacrylate, 2-Propenoic acid, 2-methyl-, (1-methylethylidene) bis (4,1-phenyleneoxy(1-methyl-2,1-ethanediyl)) ester, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	LVR	151 cP

Tera Harz TC-80DP C&B, Graphy) and a low-viscosity (LVR; C&B Permanent, ODS) polyurethane-based resin for additive manufacturing with 50-μm layer thickness. Table 1 lists detailed information on the resins tested in the present study. The viscosities of the resins were measured prior to the study by using a capillary glass viscometer (Fisherbrand Glass Opaque Calibrated Viscometer Tubes, Fischer Scientific): LVR had a viscosity of 151 cP, while HVR had a viscosity of 3,525 cP. Specimens were removed from the build platform following a 10-minute dripping time. Support structures were removed with a side cutter, and the specimens were cleaned in an ultrasonic bath of 96% ethanol (Ethanol absolut, Grogg Chemie) for 40 seconds before thorough cleaning with an ethanol-soaked (96% ethanol) cloth. Specimens were then dried with an air syringe and allowed to dry for an additional 10 minutes at room temperature to ensure that all alcohol residue was evaporated.

After printing, the specimens were randomly (Excel, Microsoft) assigned to three different polymerization units (n = 10 per group): *(1)* a xenon lamp unit (FLN; Otoflash G171, NK-Optik); *(2)* an LED unit type 1 (CLED1; Wash and Cure 2.0, Anycubic); and *(3)* an LED unit type 2 (CLED2; P Cure, Straumann). Before polymerization, color coordinate (L*, a*, and b*) measurements were performed on gray, white, and black backgrounds in a daylight-lit room using a digital spectrophotometer (CM-26d, Konica Minolta) that has the Commission International de l'Eclairage (CIE) Standard (two-degree) human observer characteristics and CIE D65 illuminant.[25] The spectrophotometer was calibrated in line with the manufacturer's instructions before the measurement of every 10 specimens, and a drop of saturated sucrose solution was used to facilitate the optical contact between the specimens and the backgrounds. For each specimen, three measurements were recorded on each background and averaged. After baseline (before polymerization) color measurements, saturated sucrose solution was cleaned from the specimens with a cloth soaked in 96% ethanol, and the specimens were polymerized using either a xenon lamp or LED units, as described in Table 2. After polymerization, color coordinates were measured again.

One surface of each specimen was ground under running water for 15 seconds for each of the silicon carbide abrasive papers used (Waterproof SIC US #280, #360, and #1000, Struers). The yellow composite polishing instrument (9104HP) of a two-step composite diamond-polishing kit (Diatech, Coltène) was used for 90 seconds at 5,000 rpm to fine-polish specimens, followed by high-gloss polishing with a polishing paste (Zircon Brite, Dental Ventures of America) and wool felt

Table 2 Polymerization Processes

Material	Cleaning process	Polymerization	
HVR (n = 30)	40 s in 96% ethanol + ethanol-soaked (96% ethanol) cloth + gently air dry	FLN (n = 10)	4,000 (2 × 2,000) flashes with 5 min of cool down between each set of exposure
		CLED1 (n = 10)	14 min: 7 min each side with 5 min of cool down between each set of exposure
		CLED2 (n = 10)	14 min: 7 min each side with 5 min of cool down between each set of exposure (upper wavelength of 420 seconds and 100% power)
LVR (n = 30)	40 s in 96% ethanol + ethanol-soaked (96% ethanol) cloth + gently air dry	FLN (n = 10)	4,000 (2 × 2,000) flashes with 5 min of cool down between each set of exposure
		CLED1 (n = 10)	14 min: 7 min each side with 5 min of cool down between each set of exposure
		CLED2 (n = 10)	14 min: 7 min each side with 5 min of cool down between each set of exposure (upper wavelength of 420 s and 100% power)

CLED1 = Wash and Cure 2.0; CLED2 = P Cure; FLN = Otoflash G171; HVR = Tera Harz TC-80DP C&B; LVR = C&B Permanent.

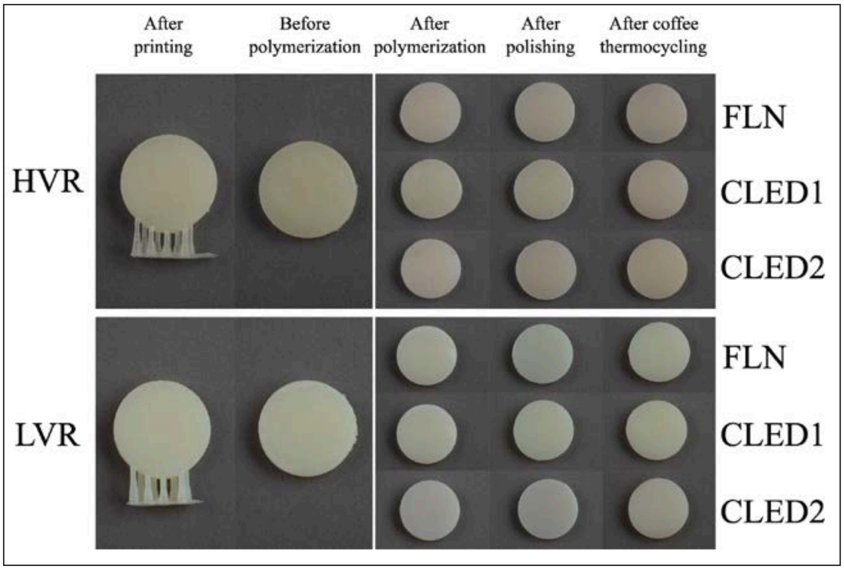

Fig 2 Representative examples of one specimen from each material–polymerization unit at each time point. CLED1 = Wash and Cure 2.0; CLED2 = P Cure; FLN = Otoflash G171; HVR = Tera Harz TC-80DP C&B; LVR = C&B Permanent.

polishing wheels (Wool felt A020422, Syndent Tools) for 90 seconds at 5,000 rpm. All specimens were then ultrasonically cleaned in distilled water for 10 minutes (Ultracleaner 07-08, Eltrosonic) and dried with paper towels, and color-coordinate measurements were repeated.

The specimens were then thermocycled in a coffee solution at 5° to 55°C (30-second dwell time, 10-second transfer time; Thermocycler, SD Mechatronik) for 5,000 cycles.[25] Coffee solution was prepared by dissolving a tablespoon of coffee grounds (Intenso Roasted and Grounded, Kaffeehof) in 177 mL of water and renewed with a freshly brewed solution in every 12 hours.[25] After coffee thermocycling, coffee extracts were removed by brushing the specimen surfaces 10 times with toothpaste (Nevadent Complex 3, DENTAL-Kosmetik). All specimens were then ultrasonically cleaned for 10 minutes and dried, and color-coordinate measurements were repeated (Fig 2). In addition, five measurements were performed 3 mm apical to the incisal edge and middle third of the facial surface[26] of the shade tab (Vita Classical Shade Guide, A1, Vita Zahnfabrik) on the gray background, and the measurements were averaged ($L^* = 68.51$, $a^* = -1.32$, and $b^* = 9.81$) to compare the color of tested resins with that of the shade tab. ΔE00 values were calculated using the coordinates measured on the gray background and the CIEDE2000 color difference formula with parametric factors (K_L, K_C, and K_H) set to 1.[25] RTP values were calculated by using the coordinates measured on white and black backgrounds (Fig 3). A single experienced operator (G.P.S) performed all specimen fabrication processes and color measurements.

Shapiro-Wilk test was used to evaluate the normality of both ΔE00 and RTP data. ΔE00 values of each material–polymerization unit pair among consecutive time points (after polymerization, after polishing, and after coffee thermocycling) were evaluated via repeated measures analysis of variance (ANOVA) with a post hoc analysis corrected by Bonferroni method. One-way ANOVA followed by Tukey honest significance difference (HSD) or Tamhane T2 (HVR after polishing and after coffee thermocycling) tests were used to evaluate the ΔE00 values of each polymerization unit within each material–time point pair. Repeated-measures ANOVA followed by Bonferroni corrected post hoc test was used to evaluate how ΔE00 values among polymerization unit pairs changed among different time points within each material. One-way ANOVA and post hoc Tukey HSD or Tamhane T2 (HVR after polishing) tests were used to evaluate the ΔE00 values among polymerization unit pairs after polymerization, after polishing, and after coffee thermocycling within each material–time point pair.

Repeated-measures nonparametric ANOVA (Friedmann test) and post hoc Dunn test were used to analyze ΔE00 values among different time points within each material–polymerization unit pair when compared to the shade tab. The effect of polymerization unit on ΔE00 values of materials after polymerization, after polishing, and after coffee thermocycling when compared to the shade tab was evaluated using either one-way ANOVA followed by Tukey HSD (HVR after polymerization and LVR after coffee thermocycling) or Tamhane T2 tests, or Kruskal-Wallis and post hoc Dunn tests (LVR after polishing).

RTP values of each material–polymerization unit pair among different time points were evaluated using either repeated-measures ANOVA with post hoc comparison with Bonferroni correction (LVR-FLN and LVR-CLED2), or Friedman test with post hoc comparison by the Dunn method. The effect of polymerization unit on RTP values of tested materials after polymerization, after polishing, and after coffee thermocycling was assessed using either one-way ANOVA and a post hoc Tukey HSD test (LVR after polymerization and after polishing) or Kruskal-Wallis test and post hoc analysis with Dunn method. All analyses were performed by using a statistical analysis software program (SPSS version 23, IBM) ($\alpha = .05$). ΔE00 values and changes in RTP values (ΔRTP) were further evaluated for perceptibility and acceptability based on previously reported thresholds: For ΔE00: ≤ 0.8 is not perceptible; ≤ 1.8 is perceptible but clinically acceptable; ≤ 3.6 is moderately unacceptable; ≤ 5.4 is clearly unacceptable; and > 5.4 units is extremely unacceptable. The thresholds for ΔRTP were 0.62 units for perceptibility and 2.62 units for acceptability.[27,28]

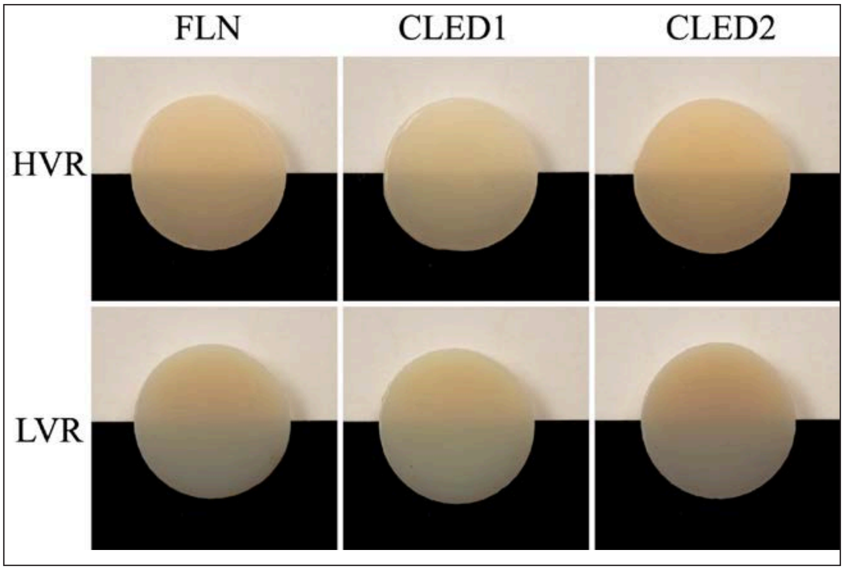

Fig 3 Representative examples showing translucency of one specimen from each material–polymerization unit after polishing. See Fig 2 legend for material and polymerization unit abbreviations.

RESULTS

Significant differences in ΔE00 values among different time points were observed for each material–polymerization unit pair and among different polymerization units for each material–time point pair (*P* ≤ .049).

Table 3 shows the values of material-polymerization unit pairs in different time points. When FLN was used, both materials had the highest ΔE00 after coffee thermocycling (*P* ≤ .040), while LVR had the lowest ΔE00 after polishing (*P* < .001). When CLED1 was used, HVR had the highest and LVR had the lowest ΔE00 after polishing (*P* ≤ .030). When CLED2 was used, HVR had higher ΔE00 after polymerization than after polishing (*P* = .032) and LVR had the lowest ΔE00 after polishing (*P* < .001). After polymerization, both materials had the highest ΔE00 when CLED2 was used and the lowest ΔE00 when CLED1 was used (*P* ≤ .005). After polishing, HVR had a higher ΔE00 when CLED1 was used than when FLN was used (*P* = .014), and LVR had the highest ΔE00 when FLN was used (*P* ≤ .021). After coffee thermocycling, both materials had the lowest ΔE00 when CLED1 was used (*P* ≤ .025). In addition, LVR had the highest ΔE00 when CLED2 was used (*P* < .001).

Table 4 shows values between polymerization units within each material. For HVR, ΔE00 of FLN–CLED1 was the highest after polymerization and after coffee thermocycling (*P* < .001), while that after polishing was higher than that before polishing (*P* = .001). ΔE00 of FLN–CLED2 was the highest after polymerization (*P* ≤ .009), and the values after polishing were greater than those before polishing (*P* = .024). ΔE00 of CLED1–CLED2 was the highest

Table 3 ΔE00 Values of Material–Polymerization Unit Pairs at Different Time Points

	After polymerization		After polishing		After coffee thermocycling	
	HVR	LVR	HVR	LVR	HVR	LVR
FLN	2.8 ± 0.5^{aB}	4.4 ± 0.2^{bB}	3 ± 0.5^{aA}	3.1 ± 0.4^{aB}	3.7 ± 0.3^{bB}	5.2 ± 0.3^{cB}
CLED1	2.0 ± 0.4^{aA}	3.1 ± 0.3^{bA}	4.1 ± 0.8^{bB}	2.5 ± 0.3^{aA}	2.4 ± 0.2^{aA}	3.0 ± 0.4^{bA}
CLED2	4.4 ± 0.7^{bC}	6.9 ± 0.3^{bC}	3.3 ± 0.4^{aAB}	2 ± 0.6^{aA}	3.4 ± 1^{abB}	6.5 ± 0.5^{bC}

Data are presented as mean ± SD.
Different superscript lowercase letters indicate significant differences among time points within each material–polymerization unit pair.
Different superscript uppercase letters indicate significant differences among polymerization units within each material–time point pair.

Table 4 ΔE00 Values Between Polymerization Units Within Each Material

	Before polymerization		After polymerization		After polishing		After coffee thermocycling	
	HVR	LVR	HVR	LVR	HVR	LVR	HVR	LVR
FLN-CLED1	0.5 ± 0.6^{a}	0.4 ± 0.2^{a}	3.5 ± 0.6^{Bc}	2.5 ± 0.6^{Ac}	1.8 ± 0.4^{Ab}	2.6 ± 0.5^{Ac}	3.0 ± 0.4^{Bc}	1.6 ± 0.3^{Ab}
FLN-CLED2	0.6 ± 0.6^{a}	0.4 ± 0.3^{a}	2.1 ± 0.5^{Ac}	2.9 ± 0.3^{Ab}	1.5 ± 0.4^{Ab}	3.1 ± 0.5^{Ab}	1.1 ± 0.4^{Aab}	2.7 ± 0.6^{Bb}
CLED1-CLED2	0.7 ± 0.6^{a}	0.5 ± 0.3^{a}	4.9 ± 0.8^{Cc}	4.3 ± 0.4^{Bb}	2.8 ± 0.8^{Bb}	5.1 ± 0.4^{Bc}	3.0 ± 0.4^{Bb}	4.2 ± 0.6^{Cb}

Data are presented as mean ± SD.
Different superscript uppercase letters indicate significant differences among different polymerization unit pairs within each material–time point pair.
Different superscript lowercase letters indicate significant differences among time points for each polymerization unit pair within each material.

Table 5 Descriptive Statistics of HVR ΔE00 Values Among Different Time Points Compared to the Shade Tab

	Before polymerization	After polymerization	After polishing	After coffee thermocycling
FLN				
Mean ± SD	11.2 ± 0.3	11.1 ± 0.6^{B}	13.6 ± 0.4^{A}	13.2 ± 0.4^{B}
Median	11.1^{ab}	10.9^{a}	13.6^{c}	13.2^{bc}
Range	11–11.8	10.1–11.9	13.2–14.3	12.6–14.1
CLED1				
Mean ± SD	11.4 ± 0.5	11.8 ± 0.6^{C}	13.5 ± 0.6^{A}	12.3 ± 0.8^{A}
Median	11.2^{a}	11.7^{a}	13.6^{b}	12.4^{ab}
Range	11–12.5	10.9–13.1	12.3–14.4	11–13.4
CLED2				
Mean ± SD	11.6 ± 0.9	10.5 ± 0.2^{A}	13.6 ± 0.4^{A}	12.5 ± 0.5^{A}
Median	11.3^{ab}	10.5^{a}	13.6^{c}	12.5^{bc}
Range	11–13.9	10.1–10.8	12.9–14.3	11.5–13.2

Different superscript lowercase letters indicate significant differences in rows. Different superscript uppercase letters indicate significant differences in columns.

after polymerization and the lowest before polymerization ($P \leq .001$). ΔE00 of CLED1–CLED2 pair was the highest after polymerization and ΔE00 of FLN–CLED2 pair was the lowest after polymerization ($P < .001$). After polishing, ΔE00 of CLED1–CLED2 was the highest ($P \leq .014$). After coffee thermocycling, ΔE00 of FLN–CLED2 was the lowest ($P < .001$). For LVR, ΔE00 of FLN–CLED1 was the highest after polymerization and after polishing ($P \leq .024$), while that after coffee thermocycling was higher than that before polishing ($P < .001$). ΔE00 values of FLN–CLED2 were the lowest before polishing ($P < .001$). ΔE00 values of CLED1–CLED2 were the highest after polishing and the lowest before polymerization ($P \leq .022$). ΔE00 of CLED1–CLED2 was the highest after polymerization, after polishing, and after coffee thermocycling ($P < .001$). In addition, ΔE00 of FLN–CLED1 was the lowest after coffee thermocycling ($P \leq .001$).

Tables 5 and 6 show descriptive statistics of ΔE00 values of HVR and LVR materials, respectively, among different time points when compared to the shade tab.

Table 6 Descriptive Statistics of LVR ΔE00 Values Among Different Time Points Compared to the Shade Tab

	Before polymerization	After polymerization	After polishing	After coffee thermocycling
FLN				
Mean ± SD	11.6 ± 0.2	11 ± 0.3^{B}	13.2 ± 0.6	13 ± 0.2^{B}
Median	11.6^{ab}	10.9^{a}	13.1^{Bc}	13^{bc}
Range	11.3–11.9	10.6–11.4	12.7–14.7	12.8–13.4
CLED1				
Mean ± SD	11.6 ± 0.2	10.2 ± 0.4^{A}	12.5 ± 0.3	12.8 ± 0.2^{A}
Median	11.6^{ab}	10.4^{a}	12.4^{Abc}	12.8^{c}
Range	11.4–11.8	9.8–10.6	12.3–13	12.4–13.2
CLED2				
Mean ± SD	11.6 ± 0.3	10.9 ± 0.6^{AB}	12.6 ± 0.5	12.9 ± 0.2^{AB}
Median	11.5^{ab}	10.8^{a}	12.7^{Abc}	13^{c}
Range	11.3–12	10.1–11.8	11.7–13.2	12.6–13.2

Different superscript lowercase and uppercase letters indicate significant differences in rows and columns, respectively.

For HVR, ΔE00 values after polymerization were the highest when CLED1 was used and were the lowest when CLED2 was used ($P \le .042$). In addition, ΔE00 values after polishing were similar among polymerization units ($P = .804$), and those after coffee thermocycling were the highest when FLN was used ($P \le .020$). When FLN was used, ΔE00 values after polishing were higher than those before and after polymerization ($P < .001$), while values after coffee thermocycling were higher than those after polymerization ($P = .034$). When CLED1 was used, ΔE00 values after polishing were higher than those before and after polymerization ($P \le .006$). When CLED2 was used, ΔE00 values after polishing were higher than those before and after polymerization ($P \le .019$), while values after coffee thermocycling were higher than those after polymerization ($P = .006$). For LVR, ΔE00 values after polymerization, and after coffee thermocycling were higher when FLN was used than when CLED1 was used ($P \le .032$). In addition, ΔE00 values after polishing were the highest when FLN was used ($P \le .043$). When FLN was used, ΔE00 values after polishing were higher than those before and after polymerization ($P \le .034$), while values after coffee thermocycling were higher than those after polymerization ($P < .001$). When CLED1 was used, ΔE00 values after coffee thermocycling were higher than those before and after polymerization ($P \le .006$), while values after polishing were higher than those after polymerization ($P = .002$). When CLED2 was used, ΔE00 values after coffee thermocycling were higher than those before and after polymerization ($P \le .011$), while values after polishing were higher than those after polymerization ($P = .001$).

Table 7 reports the descriptive statistics of RTP values of each material-polymerization unit pair after polymerization, after polishing, and after coffee thermocycling. With the exception of the RTP of HVR after polishing ($P = .480$), polymerization units affected the RTP of tested materials ($P \le .039$). After polymerization, HVR had higher RTP when CLED1 was used than when FLN was used ($P = .033$); while after coffee thermocycling, HVR had higher RTP when FLN was used than when CLED1 was used ($P = .005$). After polymerization and after polishing, LVR had the highest RTP when CLED1 was used and the lowest RTP when CLED2 was used ($P \le .048$), while FLN led to the highest RTP for LVR after coffee thermocycling ($P \le .009$). Significant differences among time points were observed within each material–polymerization unit pair ($P < .001$). When FLN was used, HVR had higher RTP after coffee thermocycling than before and after polymerization ($P \le .002$), and polishing led to higher RTP than after polymerization ($P = .006$). When CLED1 was used, RTP values were higher after polishing than before and after polymerization ($P \le .011$). When CLED2 was used, RTP values were higher after polishing and after coffee thermocycling than before and after polishing ($P \le .034$). When FLN and CLED2 were used, LVR had the highest RTP after coffee thermocycling and the lowest RTP after polymerization ($P < .001$). When CLED1 was used, RTP values were higher after coffee thermocycling than before and after polymerization ($P \le .006$). In addition, RTP values obtained after polishing were greater than the ones after polymerization ($P = .002$).

DISCUSSION

For both HVR and LVR, ΔE00 values were significantly affected by tested polymerization units and time points.

Table 7 Descriptive Statistics of RTP Values of Each Material–Polymerization Unit Pair After Polymerization, After Polishing, and After Coffee Thermocycling

		Before polymerization	After polymerization	After polishing	After coffee thermocycling
HVR					
FLN	Mean ± SD	17.2 ± 1	16.6 ± 1.1	19.5 ± 0.8	19.9 ± 0.4
	Median	17.7^{ab}	16.7^{aA}	19.8^{bcA}	20^{cB}
	Minimum–maximum	14.7–17.8	14.9–17.8	17.6–20.2	18.9–20.2
CLED1	Mean ± SD	17.3 ± 0.8	17.9 ± 1.6	19.8 ± 0.8	18.6 ± 1
	Median	17.6^{a}	17.7^{aB}	19.7^{bA}	18.6^{abA}
	Minimum–maximum	15.2–17.9	16.2–22.2	18.8–21.4	17.3–20.4
CLED2	Mean ± SD	17.3 ± 0.5	17.3 ± 0.3	20 ± 0.7	19.2 ± 0.7
	Median	17.4^{a}	17.4^{aAB}	20.1^{bA}	19.4^{bAB}
	Minimum–maximum	16–18.1	16.9–17.8	18.8–21.1	18.3–20.2
LVR					
FLN	Mean ± SD	12.1 ± 0.7^{b}	10.2 ± 0.6^{aB}	11.9 ± 0.3^{bB}	16.8 ± 0.3^{c}
	Median	12	10.3	11.9	16.8^{B}
	Minimum–maximum	11.1–12.9	9.5–10.9	11.6–12.2	16.4–17.2
CLED1	Mean ± SD	12.1 ± 0.3	11.3 ± 0.4^{C}	13 ± 0.3^{C}	15.2 ± 1.2
	Median	12.1^{ab}	11.3^{a}	12.9^{bc}	15.6^{cA}
	Minimum–maximum	11.5–12.6	10.6–11.9	12.5–13.3	12.1–16.1
CLED2	Mean ± SD	12.2 ± 0.5^{b}	9.7 ± 0.4^{aA}	11.4 ± 0.6^{bA}	16 ± 0.3^{c}
	Median	12.3	9.7	11.5	16^{A}
	Minimum–maximum	11.5–13.1	9.2–10.3	10.1–12.1	15.6–16.5

Different superscript lowercase letters indicate significant differences among time points within each material–polymerization unit pair. Different superscript uppercase letters indicate significant differences among polymerization units after polymerization, after polishing, and after coffee thermocycling.

Therefore, the first and second null hypotheses were rejected. Mean ΔE00 values of material–polymerization unit pairs ranged between 2 units (HVR–CLED1 after polymerization) and 6.9 units (LVR–CLED2 after polymerization), which can be interpreted as either moderately unacceptable, clearly unacceptable, or extremely unacceptable when these values were further evaluated according to previously reported threshold values.[27] For both resins, the CLED1 led to the lowest ΔE00 values after polymerization and after coffee thermocycling. In addition, even though CLED1 led to the highest ΔE00 values after polishing for HVR, the maximum mean ΔE00 difference among tested polymerization units was 1.1 units within this time point, which can be interpreted as perceptible but clinically acceptable.[27] The results of this study, with its limitations, may help clinicians and dental technicians to make beneficial decisions for cost-effectiveness, considering the substantial cost difference amongst tested polymerization units.

A recent study has also evaluated how coffee thermocycling affected the color stability of additively manufactured composite resins that were polymerized with FLN.[23] Those authors[23] concluded that polishing method affected the color stability of one of the tested resins and that color changes were mostly perceptible but clinically acceptable (highest mean ΔE00 value of 1.98 units). Even though FLN was used in both the present study and Çakmak et al's study,[23] the differences in tested resins and polishing methods may be associated with these contradicting results.

The third and fourth null hypotheses were also rejected, as significant differences in ΔE00 values of polymerization unit pairs were observed within and among time points for both materials. The ΔE00 values among time points within polymerization unit pairs were either significantly or nonsignificantly higher after polymerization for HVR and after polishing for LVR. This may be interpreted as tested polymerization units having a lesser effect on the polishability of HVR, as the maximum mean ΔE00 value among polymerization unit pairs was 2.8 units (CLED1–CLED2), which is moderately unacceptable. The maximum mean ΔE00 value is even smaller, just 1.8 units, and thus perceptible but clinically acceptable[27] when FLN is compared with either one of the LED curing units. However, the mean ΔE00 value among polymerization unit pairs ranged between 2.6 (moderately unacceptable) and 5.1 units (clearly unacceptable) when LVR was considered. Nevertheless, this interpretation needs to be supported with studies on the surface roughness of HVR and LVR when polymerized by tested units. The ΔE00 values of the CLED1–CLED2 pair was usually the highest, with mean values ranging between 2.8 and 5.1 units. For HVR, ΔE00 values of the FLN–CLED2 pair were usually the lowest, with mean values ranging between 0.6 and 2.1 units among the tested time points. In addition, the difference between the specimens polymerized with FLN and CLED2 decreased constantly after each time point after polymerization, and the difference was only perceptible after coffee thermocycling (ΔE00 = 1.1 units). For LVR, the ΔE00 values of the FLN–CLED1 pair were either significantly or nonsignificantly lower than those of other pairs, with means ranging between 0.4 and 2.6 units among the tested time points. Nevertheless, a similar trend to that of HVR was observed, as the difference between the specimens polymerized with FLN and CLED1 decreased constantly after each time point after polymerization and the difference was, again, only perceptible after coffee thermocycling (ΔE00 = 1.6 units). Based on these results, it can be hypothesized that FLN and CLED2 may be more suitable alternatives to each other when HVR is used, and FLN and CLED1 may be more suitable alternatives to each other when LVR is used, considering that the difference between these two polymerization units led to moderately unacceptable color differences at worst, according to reported thresholds.[27] The color differences of the specimens to be polymerized with different units were statistically similar and clinically imperceptible before polymerization; thus, the color of specimens can be considered as standardized before polymerization. However, it should also be emphasized that the mean ΔE00 values at this interval ranged between 0.4 units (FLN–CLED1 for LVR) and 0.7 units (CLED1–CLED2 for HVR), still indicating imperceptible and small color differences.

Significant differences were observed in ΔE00 values when specimens were compared to the shade tab among different time points within each material–polymerization unit pair and among polymerization units within each material–time point pair, which led to the rejection of the fifth and sixth null hypotheses. All tested material–polymerization unit pairs had extremely unacceptable color differences when compared to shade tab, regardless of the time point, with a minimum mean ΔE00 of 10.2 units (LVR–CLED1 after polymerization). However, it should be highlighted that the effect of polymerization units on the color difference of tested resins with the shade tab may be clinically negligible, considering that the greatest mean ΔE00 difference of tested resins with the shade tab before and after polymerization was 1.4 units, which is perceptible but acceptable according to previous thresholds.[27] In addition, factors other than the type of restorative material—such as its thickness, cement shade, and background color—have also been reported to affect color differences.[29] Therefore, these results should not be generalized and should be considered as preliminary given the scarcity of studies on the color differences between additively manufactured polyurethane-based resins and shade tabs. Comparisons with the shade tab were made to observe the color behavior of tested resins when the polymerization unit varied; therefore, color change takes precedence within resin, rather than considering the color difference values between resins and the shade tab. High color difference from the shade tab, regardless of the time point, is expected; it has been previously shown in color research literature that such color differences occur depending on the manufacturer, and not all restorative materials perfectly match the Vita shade guide tab colors.[30,31]

RTP values of tested resins were affected by polymerization units and time points. Therefore, the seventh and eighth null hypotheses were rejected. For HVR, the highest mean ΔRTP caused by polymerization was 1 unit (FLN), which can be interpreted as perceptible but acceptable according to reported thresholds.[28] However, polishing increased the RTP of HVR higher than the clinically acceptable threshold of 2.62 units when FLN (ΔRTP = 3.1 units) and CLED2 (ΔRTP = 2.7 units) were used. When RTP values were evaluated after coffee thermocycling, only FLN increased the RTP of HVR, but none of the changes were unacceptable. A similar trend of RTP change after polymerization was observed for LVR, as none of the polymerization units led to unacceptable differences (ΔRTP ≤ 2.6 units). Polishing perceptibly increased (ΔRTP = 1.7 units) and coffee thermocycling unacceptably increased (ΔRTP ≥ .2.7 units) the RTP of LVR, regardless of the polymerization unit. Even though a comparison among tested resins was not performed, HVR had higher RTP values than LVR regardless of the time point. This difference between HVR and LVR was also constantly noticeable.

Even though tested polymerization units have been used in previous dental studies[3,5,8,14–16,18–21] and the aim of the present study was to assess the effect of different polymerization units on the optical properties of additively manufactured resins, the fact that only three polymerization units tested was a limitation. In addition, the degree of conversion of tested resins was not investigated. Another limitation was that coffee thermocycling could not completely replicate clinical situations, as both surfaces of the specimens were discolored, and this might have amplified the color change. Saliva was not involved in the thermocycling process, and different discolorants may affect the results. The fact that only two additively manufactured polyurethane-based resins, one 3D printer, and one type of cleaning solution were used can also be considered as a limitation. Polymerization parameters were not involved in the present study, and different temperatures or durations may affect the properties of additively manufactured resins.[4,17] Finally, the disk-shaped specimens tested in the present study do not simulate clinical conditions, and optical properties may differ when tested resins are fabricated in complex geometries, such as crowns or fixed partial dentures. Future studies should investigate the effect of other parameters on the optical properties of tested additively manufactured polyurethane-based resins when different polymerization units are used, with different settings, to broaden the knowledge not only on these resins but also the applicability of third-party polymerization units on additively manufactured resins.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. When previous thresholds were considered, tested polymerization units led to unacceptable color differences for additively manufactured polyurethane-based resins after polymerization and after coffee thermocycling.
2. Resins polymerized by CLED1 (Wash and Cure 2.0) had the lowest color change after coffee thermocycling, regardless of the resin tested.
3. Tested polymerization units led to imperceptible differences in the translucency of HVR and perceptible differences in the translucency of LVR after polymerization, considering previously reported thresholds.

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