Original Article

Light Polymerization through Glass-ceramics: Influence of Light-polymerizing Unit's Emitted Power and Restoration Parameters (Shade, Translucency, and Thickness) on Transmitted Radiant Power

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Abstract

Background: This *in vitro* study assessed light transmission through ceramic discs varying in shade, translucency, and thickness using light-polymerizing units with different radiant power/flux (RP) outputs. **Methods:** Disc-shaped specimens (0.5 mm, 1.0 mm, and 2.0 mm) were made from high and low-translucency glass-ceramic ingots (IPS e.max Press) in shades A1 and A4, totaling 60 discs. Two light-polymerizing units with different power outputs were used, and their emission spectra were verified. The transmitted RP values for each ceramic specimen were measured and irradiance and radiant energy influx were calculated. Differences between the light-polymerizing units and the influence of the three ceramic parameters were evaluated using an independent-samples t-test and three-way analysis of variance (ANOVA) tests ($\alpha = 0.05$). **Results:** A statistically significant difference was observed in the mean transmitted RP values between the two light-polymerizing units. Furthermore, the three-way ANOVA test showed a significant effect of shade, translucency, and thickness, as well as a significant interaction between each pair of variables and all three variables on the transmitted RP ($P < 0.05$). **Conclusions:** Despite the significant attenuation in the transmitted RP, especially in ceramics with higher shade chromaticity and thickness and lower translucency, the calculated minimal irradiance values for both light-polymerizing units (their emitted power ≥ 500 mW) were greater than the minimum recommended irradiance threshold (100 mW/cm^2). However, the exposure duration needs to be increased to provide the resin with sufficient radiant exposure for adequate polymerization.

Keywords: *Dental polymerizing light, glass-ceramics, irradiance, radiant exposure, radiant power, resin cement*

Introduction

Resin luting cement is typically classified into three categories based on the mode of polymerization: photopolymerizing cement, which relies on light activation; chemical/autopolymerizing cement, which undergoes a chemical reaction; and dual-polymerizing cement, which involves both photo- and chemical-polymerization processes. Photopolymerizing resin cement are preferably used in esthetically critical situations because of their better initial color and color stability.[1,2] Furthermore, photopolymerizing cement are more universal because, unlike dual-polymerized cement, they give the clinician ample time to seat the restoration without an increase in viscosity due to their command set and are compatible with most adhesive systems available in the market (incompatibility exists between some adhesive systems and dual-cured resin cements).[3,4] Despite these advantages of photopolymerizing cement, the amount of light that penetrates ceramic restorations to adequately polymerize these cement is still a concern. The light reflected, absorbed, and scattered (refracted) when passing through the ceramic may lead to inadequacy in the polymerization of the photopolymerizing resin cement, which precludes the use of these cement in many clinical situations.[5-7] Moreover, a discrepancy might exist between the degree of polymerization of excess cement, which is directly exposed to the polymerization light, and the luting cement that is covered by the ceramic restoration. This discrepancy could affect

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the ease of excess cement removal, the esthetic outcomes, the durability of the restoration, and even potentially the health of adjacent tissues due to potential alterations in the cement's mechanical properties, chemical stability, and biocompatibility.[8,9]

The polymerization rate and degree of monomer-to-polymer conversion of the photopolymerizing resin cement depend on the total energy of irradiation received by the resin cement[10] (that is, radiant exposure [RE] J/cm^2, sometimes called radiant energy influx) as well as factors inherent to the resin cement itself, such as the type and concentration of the photoinitiators, viscosity, thickness, size, refractive index of filler particles, and shade.[11-13] The total energy of irradiation received by the resin cement is influenced mainly by factors related to the light-polymerizing unit (wavelength match, distance, angle, irradiance, light beam uniformity, and exposure duration)[14,15] and factors related to ceramic restoration (type, shade, translucency, and thickness).[16,17] Mathematically, RE (J/cm^2) is the product of irradiance (ratio of light-polymerizing unit radiant power/flux (RP) output to the surface area of the distal end/tip of the optical guide) received from the light-polymerization unit (mW/cm^2) and exposure duration.[18] Many previous studies have investigated the minimal emitted light irradiance of the light-polymerization unit and the RE (J/cm^2) required to initiate adequate resin polymerization, and have suggested that a minimum irradiance of 400 mW/cm^2 for 40 s (RE of 16 J/cm^2) is considered adequate for resin material polymerization.[19,20] For photopolymerizing resin luting cement, Li *et al*.[21] suggested that the minimum RE (J/cm^2) needed to provide the desired degree of polymerization is 6 J/cm^2, with a minimal irradiance of 100 mW/cm^2, as resin cement have a low film thickness (0.1 mm).

Adequate resin cement polymerization is essential for the success of bonded indirect restorations. Although many previous studies have evaluated how restoration variables impact the light transmittance of glass-ceramics during polymerization, few have taken into account the combined influence of these variables using different polymerization units. Therefore, this *in vitro* study aimed to investigate the RP of the polymerizing light emitted from two light-polymerizing units with different power outputs that passed through pressable lithium disilicate glass-ceramic discs, and the influence of ceramic thickness, translucency, and shade. The tested null hypotheses were the following: first, the power of the light polymerization units would not influence the transmitted RP that passes through the ceramic, and second, the thickness, translucency, and shade of the glass-ceramic would not influence the transmitted RP.

Methods

This study was conducted in strict compliance with the World Medical Association Declaration of Helsinki. Ethical approval for this study was granted on November 24, 2021, by Qassim University's Committee of Research Ethics, Deanship of Scientific Research (approval number "21-04-14"), following established university protocols. The glass-ceramic specimens used in this study were prepared from lithium disilicate glass ceramics ingots (IPS e.max Press, Ivoclar Vivadent AG; Schaan, Liechtenstein). Two translucencies (high translucency [HT] and low translucency [LT]) from two shades of ceramic ingots (A1 and A4) were used to prepare disc-shaped specimens with fixed diameters of 10 mm and three different thicknesses of 0.5 mm, 1 mm, and 2 mm. Five specimens were prepared from each thickness from each shade and translucency ceramic ingot with a total of 60 discs. The sample size for this study was determined using G × Power (v3.1.9.6, Heinrich Heine University Düsseldorf). With an 80% power, a significance level of 0.05, and an effect size (f: 3.43) based on Borges *et al.*,[17] adjusted for an analysis of variance (ANOVA) test involving 12 groups, a sample of 60 specimens was deemed adequate. The disc-shaped specimens were fabricated first from the inlay wax of the required thickness using a device (Ceramic sampler, Smile Line; Saint-Imier, Switzerland) [Figure 1]. Fabricated wax discs were then spruced, invested, and heat-pressed according to the manufacturer's instructions using the conventional heat-press technique. The fabrication procedure was standardized by the same technician, using the same laboratory workflow, materials, and equipment.

The specimens were then retrieved/recovered from the investment ring, and one surface of each ceramic disc was finished and polished to obtain a smooth and even surface using a ceramic finishing and polishing kit (Dialite LD System, Brasseler GmbH; Lemgo, Germany), with no glaze. The thicknesses of the discs were verified using a digital caliper. The specimens were ultrasonically cleaned in distilled water for 15 min, and the other surfaces were then etched using 5% hydrofluoric acid (IPS Ceramic Etching Gel; Ivoclar Vivadent AG; Schaan, Liechtenstein) for 20 s. Thereafter, the acid was washed, and the specimens were plot-dried.

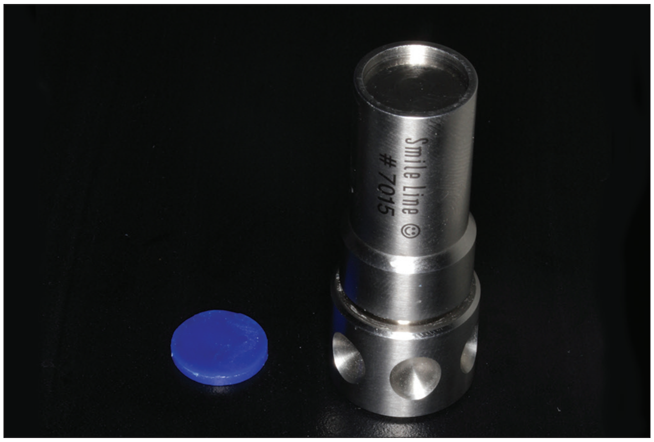

Figure 1: Fabricated wax disc using ceramic sampler

To verify the spectral output of the two light-polymerizing units used in this study (Mini LED, Acteon Group; Mérignac, France and BA Ultimate 1400, BA International; Northampton, UK) that match the spectral sensitivity of the silicon optical power detector (818-SL/DB; Newport, CA, USA), spectral emissions of the fully charged light-polymerizing units were measured using an integrating sphere connected to a fiber optic spectrometer (USB 4000, Ocean Optics; Dunedin, FL, USA). A specially customized three-dimensional-printed jig was used to align the light guide over the sphere's aperture and block ambient lighting [Figure 2]. The sphere–fiberoptic–spectrometer setup was calibrated once before the experiment using the manufacturer's calibration lamp. The polymerizing light spectral emission readings were taken three times without the ceramic specimens and three times with each specimen. OceanView v1.6.7 software (Ocean Insight, FL, USA) was used to collect and verify the spectral emission. The spectral emission was in the range of 450–550 nm, which was covered by the silicon optical power detector, with a capacity of 400–1100 nm.

RP was measured using a digital optical power meter (Model 1830-C; Newport, CA, USA) connected to an optical detector (818-SL/DB; Newport, CA, USA) with an OD3 attenuation filter according to the manufacturer's instructions, and the light-polymerizing units were fully charged and operated in rapid and normal modes for mini LED and BA ultimate, respectively. The ceramic disc specimen was first fixed/placed at the center of the aperture of the attenuator/detector using a silicone alignment jig with the polished surface facing upward. Next, the distal end of the 7.5-mm optical guide of the light-polymerizing unit was positioned over the ceramic disc (at a distance of 0 mm) through the silicone alignment jig [Figure 3] and activated for 10 s; the average RP reading display on the optical power-meter screen was recorded. The measurements for each specimen were repeated thrice with each light-polymerizing unit, and the average readings were calculated and recorded. The light-polymerizing unit was then placed back on the charging base until fully charged before it was used again for the other specimen. For the reference light-polymerizing unit's emitted RP, three measurements were performed by placing the distal end of the optical guide directly over the attenuator using the same silicone alignment jig without the interposition of ceramic discs, and the average reading was recorded. All the data were tabulated for statistical analysis. The light-polymerizing units' emitted reference irradiance and transmitted irradiance (mW/cm²) through each ceramic specimen were calculated by dividing RP (mW) by 0.64 cm^2, which corresponds to the circular surface area, where the diameter is the average width of the central incisor (9 mm). Furthermore, to verify the adequacy of the polymerization power, RE (J/cm²) was calculated by dividing RP (mW) by 1000 to obtain the value in Watt (W) and then by multiplying the resultant value by 20 s.

Statistical analysis

Welch's *t*-test and three-way ANOVA were conducted to inspect the differences between the two light-emitting diode units and to determine the effects of ceramic shade, translucency, and thickness on the transmitted RP. Data were presented as mean ± standard deviation unless otherwise stated. All groups of independent variables were normally distributed ($P > 0.05$) as assessed using Shapiro–Wilk's test of normality. The assumption of homogeneity of variances was violated for the *t*-test. There was homogeneity of variances for the three-way ANOVA test, as assessed by Levene's test for equality of variances ($P = 0.011$ and $P = 0.957$, respectively). Statistical analysis was performed using the statistical software program (IBM SPSS Statistics, v20.0; IBM Corp) ($\alpha=0.05$).

Results

The descriptive statistics obtained for the transmitted RP, irradiance, and RE are shown in Table 1. There was a statistically significant difference in the mean transmitted

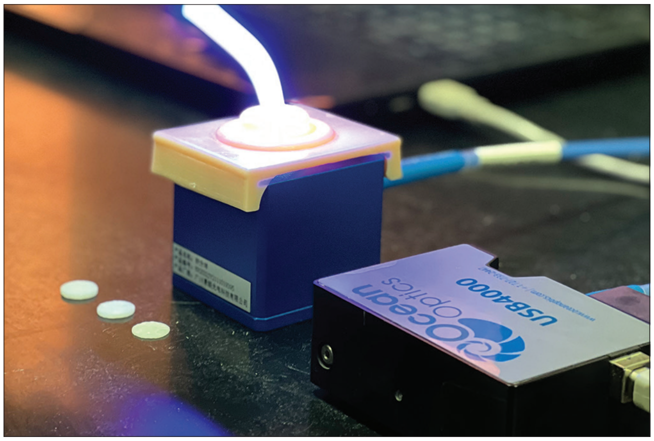

Figure 2: Verification of light-polymerizing unit emission spectrum using fiber optic spectrometer with the alignment jig

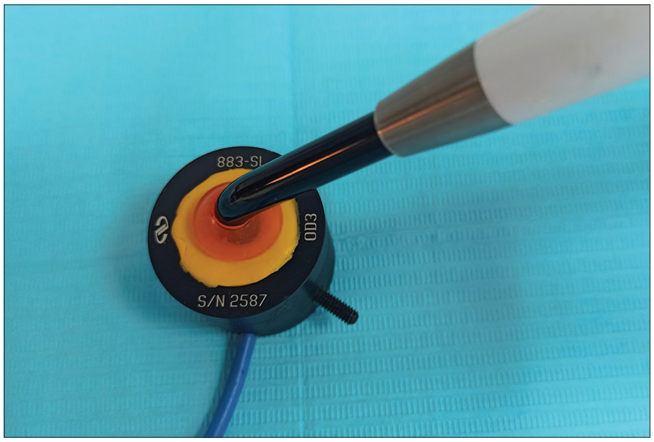

Figure 3: Placement of light-polymerizing unit's optical guide over the OD3 attenuation filter of the optical detector with interposing of the ceramic specimen using silicone alignment jig

RP values between the two light-emitting diode units, with Mini_led scoring higher than BA_ultimate (62 mW [95% confidence interval: 36–88], *t* [4.689] = 6.761, $P < 0.001$). Three-way ANOVA for both light-polymerizing units revealed that all three factors, including the ceramic shade ($P < 0.001$), translucency ($P < 0.001$), and thickness ($P < 0.001$), significantly influenced the transmitted RP. The two-way interactions between

Table 1: Descriptive statistics

Shade	Translucency	Thickness (mm)	Mini_led				BA_ultimate			
			Radiant power (mW)	Percentage of radiant power (mW) from reference emitted power (%)*	Irradiance for 9 mm diameter circle (mW/cm²)	Radiant exposure for 20 s (J/cm²)	Radiant power (mW)	Percentage of radiant power (mW) from reference emitted power (%)*	Irradiance for 9 mm diameter circle (mW/cm²)	Radiant exposure for 20 s (J/cm²)
A1	HT	0.5	409 (8.9)	60	643	12.9	307 (6.7)	62	483	9.7
		1.0	359 (5.3)	53	564	11.3	270 (4.2)	55	424	8.5
		2.0	283 (6.5)	41	445	8.9	212 (4.8)	43	333	6.7
	LT	0.5	327 (5.3)	48	514	10.3	246 (4.2)	50	387	7.7
		1.0	277 (6.5)	41	435	8.7	209 (4.9)	42	329	6.6
		2.0	202 (5.6)	30	318	6.4	151 (4.2)	31	237	4.7
A4	HT	0.5	235 (5.0)	34	369	7.4	177 (5.1)	36	278	5.6
		1.0	208 (5.5)	30	327	6.5	156 (4.2)	32	245	4.9
		2.0	158 (4.8)	23	248	5.0	119 (3.8)	24	187	3.7
	LT	0.5	197 (5.3)	29	310	6.2	148 (4.1)	30	233	4.7
		1.0	173 (4.4)	25	272	5.4	129 (1.6)	26	203	4.1
		2.0	141 (5.1)	21	222	4.4	104 (3.8)	21	163	3.3

*Reference emitted radiant power: Mean 683 mW for Mini_Led and 492 mW for BA_Ultimate. HT: High translucency; LT: Low translucency

Table 2: Summary of results of a three-way analysis of variance results of transmitted radiant power (mW), according to the ceramic shade, translucency, and thickness for both light-polymerizing units

Light-polymerizing unit	Source	Type III sum of squares	df	Mean square	*F*	*P*	η_p^2
Mini_Led	Corrected model	390,599.783[a]	11	35,509.071	1059.182	<0.001*	0.996
	Intercept	3,674,880.017	1	3,674,880.017	109,616.108	<0.001*	1.000
	Shade	231,260.417	1	231,260.417	6898.148	<0.001*	0.993
	Translucency	45,982.017	1	45,982.017	1371.574	<0.001*	0.966
	Thickness	93,424.133	2	46,712.067	1393.350	<0.001*	0.983
	Shade × translucency	10,166.017	1	10,166.017	303.237	<0.001*	0.863
	Shade × thickness	9104.533	2	4552.267	135.787	<0.001*	0.850
	Translucency × thickness	361.733	2	180.867	5.395	0.008*	0.184
	Shade × translucency × thickness	300.933	2	150.467	4.488	0.016*	0.158
	Error	1609.200	48	33.525			
	Total	4,067,089.000	60				
	Corrected total	392,208.983	59				
BA_Ultimate	Corrected model	222,307.133[b]	11	20,209.739	1025.875	<0.001*	0.996
	Intercept	2,066,099.267	1	2,066,099.267	104,878.135	<0.001*	1.000
	Shade	131,601.667	1	131,601.667	6680.288	<0.001*	0.993
	Translucency	26,628.267	1	26,628.267	1351.689	<0.001*	0.966
	Thickness	53,529.233	2	26,764.617	1358.610	<0.001*	0.983
	Shade × translucency	5377.067	1	5377.067	272.948	<0.001*	0.850
	Shade × thickness	4860.633	2	2430.317	123.366	<0.001*	0.837
	Translucency × thickness	165.233	2	82.617	4.194	0.021*	0.149
	Shade × translucency × thickness	145.033	2	72.517	3.681	0.033*	0.133
	Error	945.600	48	19.700			
	Total	2,289,352.000	60				
	Corrected total	223,252.733	59				

*The mean difference is significant at the 0.05 level; [a]R^2=0.996 (adjusted R^2=0.995); [b]R^2=0.996 (adjusted R^2=0.995);
ηp^2=Partial Eta Squared.

ceramic shade, translucency, and thickness were statistically significant ($P \leq 0.05$). In addition, the interaction between the three factors was also statistically significant ($P \leq 0.05$) [Table 2].

There was a statistically significant ($P = 0.001$) simple two-way interaction between thickness and translucency for A4 ceramic shade in both shade groups for Mini_led and BA_ultimate units, but not for A1 ceramic shade ($P = 0.899$ and $P = 0.99$, respectively) [Figure 4].

Furthermore, one-way main effect analyses for the data of both light-polymerizing units were performed, and a statistical significance was accepted at $P < 0.025$. The simple main effect revealed a significant effect of translucency on the recorder-transmitted RP values. Pairwise comparisons showed significantly lower transmitted RP values for the LT specimens than for the HT specimens ($P < 0.001$). The ceramic thickness also had a significant effect on the transmitted RP values. Moreover, pairwise comparisons showed that the lowest transmitted light power values were recorded for the 2-mm thickness, followed by those for the 1-mm and 0.5-mm, and the differences were significant between each pair of ceramic thicknesses [Table 3]. Finally, the differences between the means of the transmitted RP values between the A1 and A4 ceramic shades were also significant. The A4 shade specimens recorded the lowest power values in comparison with the A1 shade specimens ($P < 0.001$) [Table 4].

Discussion

Both null hypotheses were rejected because of the statistically significant difference between the two light-polymerizing units in transmitted light power values and the significant effect of the three ceramic variables and their interactions on the transmitted light values.

A significant reduction in the transmitted RP values was observed when the light passed through the ceramic specimens, and the transmitted power values were in the range of 20%–60% of the incident polymerizing light for both polymerizing units. However, the transmitted RP percentages observed in this study were higher than those reported in most previous studies that examined the same material. Flury *et al*.[22] reported only 14% transmitted irradiance through 1.5-mm A3 shade IPS e.max CAD discs. These differences may be due to the specimen fabrication technique, the use of glazes in previous studies, the use of other light units, and the use of different power meter sensors.

The results of this study show differences in the transmitted RP between different ceramic translucencies with significantly higher transmitted light power in all HT specimens when compared with their low-translucency counterparts using the same shade and thickness, which is consistent with the results of many studies.[23,24] However,

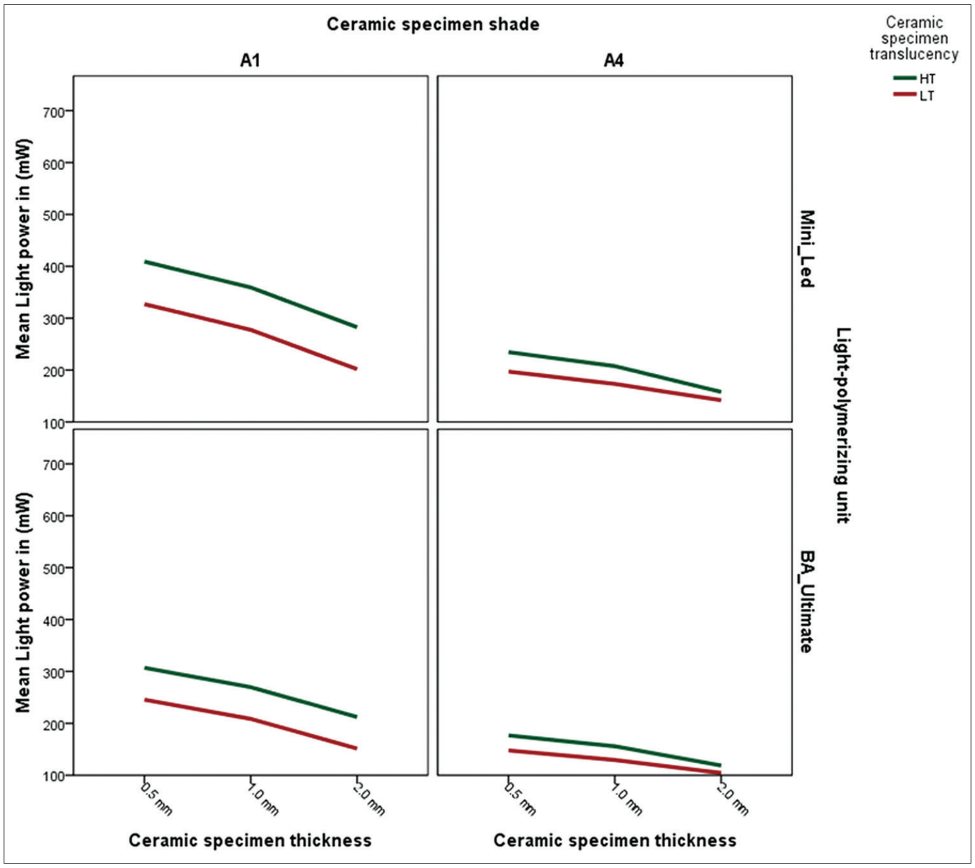

Figure 4: Line chart showing transmitted radiant power among different ceramic shades, translucency, and thickness for both light-polymerizing units

Table 3: Pairwise comparison of mean change in transmitted radiant power (mW) between the two shades for both light-polymerizing units

Light-polymerizing unit	Ceramic specimen translucency	Ceramic specimen thickness (mm)	(I) ceramic specimen shade	(J) ceramic specimen shade	Mean difference (I−J)	SE	$P^{\wedge b}$	95% CI	
								Lower	Upper
Mini_Led	HT	0.5	A1	A4	174.400*	3.662	<0.001*	167.037	181.763
			A4	A1	−174.400*	3.662	<0.001*	−181.763	−167.037
		1.0	A1	A4	151.600*	3.662	<0.001*	144.237	158.963
			A4	A1	−151.600*	3.662	<0.001*	−158.963	−144.237
		2.0	A1	A4	124.600*	3.662	<0.001*	117.237	131.963
			A4	A1	−124.600*	3.662	<0.001*	−131.963	−117.237
	LT	0.5	A1	A4	130.200*	3.662	<0.001*	122.837	137.563
			A4	A1	−130.200*	3.662	<0.001*	−137.563	−122.837
		1.0	A1	A4	104.200*	3.662	<0.001*	96.837	111.563
			A4	A1	−104.200*	3.662	<0.001*	−111.563	−96.837
		2.0	A1	A4	60.000*	3.662	<0.001*	52.637	67.363
			A4	A1	−60.000*	3.662	<0.001*	−67.363	−52.637
BA_Ultimate	HT	0.5	A1	A4	130.400*	2.807	<0.001*	124.756	136.044
			A4	A1	−130.400*	2.807	<0.001*	−136.044	−124.756
		1.0	A1	A4	113.800*	2.807	<0.001*	108.156	119.444
			A4	A1	−113.800*	2.807	<0.001*	−119.444	−108.156
		2.0	A1	A4	93.600*	2.807	<0.001*	87.956	99.244
			A4	A1	−93.600*	2.807	<0.001*	−99.244	−87.956
	LT	0.5	A1	A4	97.800*	2.807	<0.001*	92.156	103.444
			A4	A1	−97.800*	2.807	<0.001*	−103.444	−92.156
		1.0	A1	A4	79.400*	2.807	<0.001*	73.756	85.044
			A4	A1	−79.400*	2.807	<0.001*	−85.044	−73.756
		2.0	A1	A4	47.000*	2.807	<0.001*	41.356	52.644
			A4	A1	−47.000*	2.807	<0.001*	−52.644	−41.356

Based on estimated marginal means, *The mean difference is significant at the 0.05 level; ^{b}Adjustment for multiple comparisons: Bonferroni. CI: Confidence interval, HT: High translucency; LT: Low translucency

the difference between LT and HT in the A1 shade was uniform in the three thicknesses at around 12%, which is much higher than the data reported by Oh *et al*.[16] (around 5% for the A2 shade). Furthermore, the effect of translucency in A4 specimens varied according to the specimen's thickness, and this effect was less pronounced in 2-mm thickness specimens, as shown in the pairwise comparison table, where the difference between LT and HT was only 3%, which is may be due to decrease in translucency of the ceramic materials as the thickness increase, especially in dark shades.[25]

When the thicknesses are compared, the expected thickness also has a significant effect on the amount of transmitted RP. With an inverse relationship, the transmitted RP values decrease exponentially as the ceramic thickness increases, which is in agreement with those obtained by other authors.[26] The differences between 0.5-mm thickness and 2.0-mm thickness in the A1 shade were around 18%, which are close to the values reported by Borges *et al*.[17] (16% and 25% for HT and LT, respectively) and Oh *et al*.[16] (14%). However, in the A4 shade, the thickness effect was lesser and in the range of 8%–11%. Therefore, thickness is an important factor to consider when using glass ceramics as a veneering material or crown over opaque sub-structures such as polyetheretherketone formulations like BioHPP. This is because it is necessary to mask the underlying color in order to match the adjacent natural teeth color and translucency while also allowing enough polymerization light to pass through to sufficiently photopolymerize the luting resin.[27]

The effect of shade was the most pronounced among the three variables because of the large color difference between A1 and A4 shades. Lighter A1 shade ceramic specimens allowed higher transmitted RP to pass and reach the resin cement as compared to darker A4 specimens of the same thickness and translucency, which is in agreement with previous studies.[28] The poorest specimens in terms of transmitted RP were the A4 low-translucency 2-mm thick specimens; however, the minimal irradiance required to polymerize the resin cement was achieved in both polymerizing lights (≥100 mW/cm^2). Surprisingly, these findings are not in agreement with those of another study (Borges *et al*. study),[17] which reported that the darker shade A3.5 allowed greater light transmission than shade A1.

There was a direct relationship between the incident power output of the light-polymerizing unit and the transmitted

Table 4: Pairwise comparison of mean change in transmitted radiant power (mW) among 3 thicknesses for both light-polymerizing units

Light-polymerizing unit	Ceramic specimen shade	Ceramic specimen translucency	(I) ceramic specimen thickness (mm)	(J) ceramic specimen thickness	Mean difference (I−J)	SE	*P*	95% CI	
								Lower	Upper
Mini_Led	A1	HT	0.5	1.0	49.800*	3.662	<0.001*	40.715	58.885
				2.0	126.400*	3.662	<0.001*	117.315	135.485
			1.0	0.5	−49.800*	3.662	<0.001*	−58.885	−40.715
				2.0	76.600*	3.662	<0.001*	67.515	85.685
			2.0	0.5	−126.400*	3.662	<0.001*	−135.485	−117.315
				1.0	−76.600*	3.662	<0.001*	−85.685	−67.515
		LT	0.5	1.0	49.600*	3.662	<0.001*	40.515	58.685
				2.0	125.400*	3.662	<0.001*	116.315	134.485
			1.0	0.5	−49.600*	3.662	<0.001*	−58.685	−40.515
				2.0	75.800*	3.662	<0.001*	66.715	84.885
			2.0	0.5	−125.400*	3.662	<0.001*	−134.485	−116.315
				1.0	−75.800*	3.662	<0.001*	−84.885	−66.715
	A4	HT	0.5	1.0	27.000*	3.662	<0.001*	17.915	36.085
				2.0	76.600*	3.662	<0.001*	67.515	85.685
			1.0	0.5	−27.000*	3.662	<0.001*	−36.085	−17.915
				2.0	49.600*	3.662	<0.001*	40.515	58.685
			2.0	0.5	−76.600*	3.662	<0.001*	−85.685	−67.515
				1.0	−49.600*	3.662	<0.001*	−58.685	−40.515
		LT	0.5	1.0	23.600*	3.662	<0.001*	14.515	32.685
				2.0	55.200*	3.662	<0.001*	46.115	64.285
			1.0	0.5	−23.600*	3.662	<0.001*	−32.685	−14.515
				2.0	31.600*	3.662	<0.001*	22.515	40.685
			2.0	0.5	−55.200*	3.662	<0.001*	−64.285	−46.115
				1.0	−31.600*	3.662	<0.001*	−40.685	−22.515
BA_Ultimate	A1	HT	0.5	1.0	37.400*	2.807	<0.001*	30.436	44.364
				2.0	94.800*	2.807	<0.001*	87.836	101.764
			1.0	0.5	−37.400*	2.807	<0.001*	−44.364	−30.436
				2.0	57.400*	2.807	<0.001*	50.436	64.364
			2.0	0.5	−94.800*	2.807	<0.001*	−101.764	−87.836
				1.0	−57.400*	2.807	<0.001*	−64.364	−50.436
		LT	0.5	1.0	37.000*	2.807	<0.001*	30.036	43.964
				2.0	94.200*	2.807	<0.001*	87.236	101.164
			1.0	0.5	−37.000*	2.807	<0.001*	−43.964	−30.036
				2.0	57.200*	2.807	<0.001*	50.236	64.164
			2.0	0.5	−94.200*	2.807	<0.001*	−101.164	−87.236
				1.0	−57.200*	2.807	<0.001*	−64.164	−50.236
	A4	HT	0.5	1.0	20.800*	2.807	<0.001*	13.836	27.764
				2.0	58.000*	2.807	<0.001*	51.036	64.964
			1.0	0.5	−20.800*	2.807	<0.001*	−27.764	−13.836
				2.0	37.200*	2.807	<0.001*	30.236	44.164
			2.0	0.5	−58.000*	2.807	<0.001*	−64.964	−51.036
				1.0	−37.200*	2.807	<0.001*	−44.164	−30.236
		LT	0.5	1.0	18.600*	2.807	<0.001*	11.636	25.564
				2.0	43.400*	2.807	<0.001*	36.436	50.364
			1.0	0.5	−18.600*	2.807	<0.001*	−25.564	−11.636
				2.0	24.800*	2.807	<0.001*	17.836	31.764
			2.0	0.5	−43.400*	2.807	<0.001*	−50.364	−36.436
				1.0	−24.800*	2.807	<0.001*	−31.764	−17.836

Based on estimated marginal means, *The mean difference is significant at the 0.05 level. Adjustment for multiple comparisons: Bonferroni. CI: Confidence interval; HT: High translucency; LT: Low translucency light power. Therefore, using a higher power output light-polymerizing unit may be advantageous during the photopolymerization of cement under thick, dark, and low-translucency ceramic restorations. The lowest average transmitted irradiance for the 2-mm thick A4 low-translucency ceramic specimens was 163 mW/cm^2 in the BA_ultimate unit group. This value exceeds the minimal irradiance value reported by Li *et al.*[21] (100 mW/cm^2); however, the RE of transmitted light was lesser than the recommended energy needed to adequately polymerize the resin (6 J/cm^2) as the average RE calculated was only 3.3 J/cm^2 when the exposure duration was 20 s. Even though the reciprocity law cannot be always applied,[29,30] in this case, the minimal irradiance value was not violated (>100 mW/cm^2),[31] and therefore, an increase in the exposure duration to 40 s ensured the delivery of a minimal RE of 6 J/cm^2, which is sufficient for resin polymerization. This result is supported by Faria-e-Silva and Pfeifer[32] who reported that using standard-mode light-polymerizing units to polymerize cement through a 2-mm thick ceramic resulted in an acceptable resin cement degree of conversion, with no significant difference from cement that polymerized without an intervening ceramic specimens. In their study, they used a 20 s exposure duration; however, the transmitted irradiance was in the range of 312–356 (mW/cm^2) (i.e., RE in the range of 6–7 J/cm^2).

The results of this study highlight the effects of shade, translucency, and thickness on light transmittance, as well as the values and percentages of light attenuation, during the polymerization of luting resin cement through glass-ceramic restorations of varying shades, translucencies, and thicknesses. These findings can guide clinicians in the selection of the appropriate type of cement and polymerization protocols. In accordance with the reciprocity principle,[10,32] when applicable. Furthermore, the selection of a polymerization light unit should consider not only adequate irradiance but also the unit's radiant power and the active tip diameter of the light guide used.[11]

It is crucial to note that some manufacturers of budget polymerizing units may use a small diameter light guide to boost the unit's irradiance while actually using a low-power LED light.[11] This approach can result in the irradiance falling short of the recommended level (100 mW/cm^2) when polymerizing the surface of large indirect restorations with a single light exposure cycle. Therefore, clinicians should be aware of these factors when selecting a light-polymerizing unit.

This study attempted to replicate an authentic laboratory workflow for creating pressable ceramic specimens and standardized RP measurements. However, some limitations should be noted. The polymerization efficacy of dental light units is dependent not only on the RP values but also on the uniformity of the emitted light beam and their spectral power distribution,[33] which were not assessed in this study. In addition, the impact of transmitted light on the resin cement's degree of monomer-to-polymer conversion and physical behavior was not evaluated. These may be considered limitations. Furthermore, there is a need to establish a consensus regarding the minimal irradiance and RE required to optimally polymerize contemporary resin cement containing various photoinitiators. Consequently, further research is necessary for gaining a deeper understanding of the light-polymerizing process and the effects and interactions of the light units, bonded restoration, and resin cement factors. This would facilitate evidence-based clinical decision-making during the cementation step using photopolymerizing resin cement, ultimately leading to better clinical performance.

Conclusions

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

1. The ceramic restoration shade, translucency, and thickness have a significant effect on the amount of transmitted RP that reaches the resin cement
2. The transmitted RP reduction was 40%–79% and ranked as follows: A1 > A4 (shade); HT > LT (translucency); 0.5 mm >1.5 mm >2.0 mm (thickness)
3. The calculated minimal transmitted irradiance values through the ceramic specimens for both light-polymerizing units (their emitted radiant power ≥500 mW) were greater than the minimum recommended irradiance threshold (100 mW/cm^2). However, clinicians should consider increasing the exposure duration, especially for dark and thick ceramic restorations, so that the resin receives adequate RE.

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Conflicts of interest

There are no conflicts of interest.

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