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Original Article

Relationship between the polymerization distance of monowave and polywave light-curing units and the irradiance and physical properties of dental resin-based composites

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Abstract

Purpose: To evaluate the influence of the polymerization distance of monowave and polywave light curing units (LCUs) on the measured irradiance relative to the value reported by the manufacturer in relation to the physical properties of resin-based composites (RBCs).
Methods: Four LCUs were used: one monowave and three polywave. The irradiance was measured with a digital radiometer. Depth of cure (DC) and flexural strength (FS) tests were performed according to ISO 4049:2019 at polymerization distances of 0 mm and 5 mm.
Results: The irradiance of all LCUs was higher than that reported by the manufacturer (>25-64%). The irradiance of the four LCUs was reduced when polymerization was performed at between 0 to 5 mm (paired *t*-test, $P < 0.001$). The DC at 0 mm was similar in all groups but was significantly decreased at 5 mm distance (ANOVA $P < 0.001$). FS showed differences among the LCUs at 0 mm (ANOVA $P < 0.001$) and was affected by the polymerization distance. The elastic modulus was unaffected by the LCU used or the distance (ANOVA $P > 0.001$).
Conclusions: The LCU must be positioned as near as possible to RBCs during the polymerization process, as increased distance negatively affects the depth of cure and flexural strength.

Keywords: depth of cure, flexural strength, irradiance, light curing unit, resin-based composite

Introduction

Dental resin-based composites (RBCs) are currently the most frequently used restorative material in dentistry, mainly because of their versatility for indications such as direct restoration, luting, and pit and fissure sealing [1]. Their basic composition includes an organic matrix, an inorganic matrix or filler, and a coupling agent. The organic matrix contains methacrylate monomers such as bisphenol A-glycidyl methacrylate (Bis-GMA), ethoxylated bisphenol A-glycol dimethacrylate (Bis-EMA), triethylene glycol dimethacrylate (TEGDMA), hydroxyethyl methacrylate (HEMA), and urethane dimethacrylate (UDMA) [2]. The inorganic filler is made up of particles (quartz, glass, colloidal silica, hydroxyapatite [3] fiberglass [4]) of different sizes (0.4-1.0 μm to 5-100 nm) that provide wear resistance, polishing, esthetic and mechanical properties, and these are coated with coupling agents such as zirconate, titanate, and silanes [2,5] to bond them to the organic matrix.

In most cases, RBCs require light for photoinitiation to polymerize the organic matrix [2]. The most common photoinitiator is camphorquinone (CQ), but alternative photoinitiators such as 1-phenyl-1,2-propanedione (PPD) and trimethylbenzoyl-diphenylphosphine oxide (TPO) have also been incorporated to confer a higher color value [6]. Recently, a new technology known as radical amplified photopolymerization (RAP) has been incorporated in some dental resin composites. This allows the RC to be polymerized in a shorter time with a reduced amount of CQ, as CQ is recycled [7]: according to the manufacturer, “a single CQ molecule can produce multiple initiator radicals”.

Polymerization occurs when the photoinitiator produces free radicals, which break the carbon-carbon double bond (C=C, bond energy 614 kJ/mol) into a carbon-carbon single bond (C-C) in a chain reaction until two free radicals reacts with each other [2,8]. A photoinitiator must be capable of absorbing visible light to initiate this reaction, generally at a wavelength of 400-480 nm [2]. Light-curing units (LCUs) are an important dental device for the RBC polymerization process, and currently the LCU light source is a light-emitting diode (LED), which is efficient and cost-effective [9].

In the early 2000s, second-generation LED LCUs were introduced, incorporating a single powerful LED with a spectral emission of 460-480 nm [1,8] and a unique emission peak corresponding to the major absorption peak of CQ (468 nm) [9,10]. These LCUs are referred to as monowave or mono-peak LCUs. Later, alternative photoinitiators such as TPO and PPD with maximum absorption peaks at 400 and 410 nm, respectively, were introduced as a third generation known as polywave or multipeak LCUs, incorporating different wavelength chips to provide a simultaneous combination of ultraviolet and blue lights with wavelengths of 400 and 460 nm, respectively [8-10].

Several factors are necessary to achieve optimal polymerization. Some are related to the RBCs, such as viscosity [11], filler percentage [5,12], photoinitiator type [12,13], and color [14,15], whereas others are related to the LCUs, such as exposure time [16,17], tip diameter [18], irradiance [17], and radiant power [8,10]. Incomplete polymerization may result in inferior mechanical properties, lower wear resistance, color change or brightness loss. The aim of the present study was to evaluate the influence of the polymerization distance of monowave and polywave LCUs on the measured irradiance relative to the irradiance reported by the manufacturer, as well as the physical properties of the RBC.

Materials and Methods

Four LED LCUs were used: one monowave and three polywave (Table 1). The RBC used was an opaque color (Palfique LX5, Tokuyama Dental, Tokyo, Japan).

Emission spectra and irradiance measurement

Measurements of the LCUs were carried out using a spectrofluorometer (NanoLog, Horiba, CA, USA) with the LCU as a light source reflected from a mirror placed at 45° to obtain the emission spectrum of the lamp. An imaging spectrometer (Horiba iHR320, Horiba, CA, USA) coupled to the spectrofluorometer was used to scan at wavelengths of 350-550 nm using slits with an optical width of 0.1 nm and an acquisition speed of 600 nm/min. A circular limiting grid 0.8 mm in diameter was placed on the external surface of the lamp to reduce the intensity of the emission and the risk of damaging the equipment’s detectors.

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Table 1 Information on the light curing units (LCUs) and the resin composite used in this study

LCU	Manufacturer	Light tip	Diameter tip (mm)	Connection type	Polywave/Monowave	Manufacturer's stated irradiance (mW/cm²)
Bluephase N MC	Ivoclar Vivadent, Austria	filament	10	Wired	Monowave	800
Bluephase N	Ivoclar Vivadent, Austria	filament	10	Wireless	Polywave	Low power: 650
Nano	COXO, P. R. China	direct	11	Wireless	Polywave	1,100-1,200
VALO	Ultradent Products Inc. UT, USA	direct	9.6	Wired	Polywave	Standard power: 1,000
Resin composite	Manufacturer	Organic matrix		Inorganic matrix	Photoinitiator system	
Palfique LX5, Color OA2, Batch 186EZ1	Tokuyama Dental, Tokyo, Japan	BisGMA, TEGDMA		82% by weight or 71% by volume of spherical submicron silica-zirconia filler (mean particle size 0.2 µm, range of particle size 0.1-0.3 µm)	Camphorquinone with RAP technology	

Before irradiance measurement, each LCU was fully charged overnight to ensure maximum efficiency. The irradiance (mW/cm²) of each LCU was measured with a digital radiometer for LED light (Bluephase Meter II, Ivoclar Vivadent, Austria) with a measuring irradiance range of 50-3,600 mW/cm² and a wavelength of 350-550 nm. The light curing tip was fully attached to the measuring surface at a distance of 0 mm or 5 mm and activated for 20 s (n = 15 for each LCU and distance). Finally, the energy density was calculated using the formula:

$$\frac{mW/cm^2}{1{,}000} \times exposure\ time = J/cm^2$$

Where mW/cm² is the measured irradiance for each lamp at 0 and 5 mm, with an exposure time of 20 s.

Depth of cure

The depth of cure was determined according to the ISO 4049:2019 standard [19] using cylindrical samples prepared (n = 10, for each LCU and distance) with stainless steel molds (diameter 4 mm and height 6 mm). The molds were placed above a microscope slide and polyethylene sheet, then filled with the resin composite (Palfique LX5) in one increment. The mold was fully filled, and the resin composite was condensed to avoid any air inclusion. Then a polyethylene sheet was place on the upper surface of the mold and the light tip guide of each LCU was placed either in direct contact with the resin composite (corresponding to a distance of 0 mm) or at a distance of 5 mm, followed by irradiation for 20 s. The resin composite sample was removed from the stainless steel mold, and the lower non-polymerized surface of the sample was eliminated using a plastic spatula. The remaining polymerized sample was measured with a digital micrometer (Mitutoyo Micrometer, Digimatic, Tokyo, Japan), and then the obtained value was divided by two and registered as the depth of cure. The bottom non-polymerized surface of all samples was sputter-coated with gold for scanning electron microscopy (SEM) observation in low vacuum mode at a pressure of 15 Pa with backscattered electrons at 20 kV (JSM5600-LV, Jeol, Tokyo, Japan) at ×200 magnification.

Flexural strength

For three-point flexural strength test, stainless steel molds (2 mm × 2 mm × 25 mm) were used for sample preparation according to the ISO 4049:2019 [19] standard (n = 10). The mold was placed above a microscope slide and polyethylene sheet to obtain a flat, smooth surface. The molds were filled with one increment of the resin composite and covered with a second polyethylene sheet and microscope slide, applying a slight pressure to flat the upper surface. The whole preparation was pressed with a mini-clamp to extrude any excess material. The upper microscope slide was then removed, and polymerization was performed with 5 overlapping points on the superior side of the sample for each LCU type and distance (0 or 5 mm), and this process was repeated on the lower side of the sample. Specimens were then removed from the mold, and softly polished with 320-grit silicon carbide paper, avoiding the top or bottom surfaces. The samples were stored in distilled water (Hycell Chemical Reactives, Guadalajara, Mexico) at 37°C for 24 h (Felisa Stove, Guadalajara, Mexico), then removed and measured with a micrometer at the center. Any samples with air inclusion or gaps were discarded. The top surface was identified (first polymerized surface) as it had become the lower side during the flexural strength test, corresponding to the tension side. Each sample was placed on the test jig (with the characteristics specified for ISO 4049-2019) of a universal mechanical testing machine (Instron 5567, Instron, Norwood, MA, USA) with a cross-head speed of 0.75 mm/min until the sample fractured. The flexural strength and elastic modulus were recorded in MPa and GPa, respectively. Flexural strength was calculated using the formula:

$$\sigma = \frac{3FL}{2bh^2}$$

where F represents the maximum force; L the distance between the supports; b the width of the specimen, and h the specimen height. The Young's modulus of elasticity was calculated according to the formula:

$$E = \frac{FL^3}{4bh^3d}$$

where d represents the deflection of the specimen according to the load F.

Statistical analysis

The means and standard deviations were calculated for each test. Shapiro-Wilks test was used to analyze the normality of the data. As irradiance did not show a normal distribution (P = 0.021), Mann-Whitney U test was used to compare irradiance relative to distance. As depth of cure (P = 0.397), flexural strength (P = 0.697), and elastic modulus (P = 0.418) showed a normal distribution, paired t-test was used to compare each lamp at distances of 0 and 5 mm. Levene test was used to analyze the homoscedasticity of the data (depth of cure P = 0.243; flexural strength P = 0.174; elastic modulus P = 0.866). Analysis of variance (ANOVA) and multiple comparison *post hoc* Tukey test were used for comparisons between lamps. The analyses were performed using IBM SPSS Statistics software version 21 (Statistical Package for the Social Sciences, Chicago, IL, USA) and α = 0.05 was the cutoff for statistical significance in all tests.

Results

Measurement of emission spectra and irradiance

The emission spectra of each LCU showed that (Fig. 1) Bluephase N MC had a wavelength range of 415-500 nm, being a monowave LCU with a unique maximal peak at 450 nm. The other three LCUs were polywave; Bluephase N shows a wavelength of 380-510 nm, with two maximal signal peaks at 410 and 455 nm. The Nano COXO emission spectrum was 385-495 nm with two signals: the highest at 449 nm and the weakest at 410 nm. Finally, VALO showed a wide wavelength range of 365-510 nm, with signal peaks at 390, 445 and 460 nm.

The manufacturers' stated irradiance values were compared with those obtained in this study at 0 and 5 mm from each LCU. This revealed that the irradiance of all LCUs was greater than that indicated by the manufacturer (Table 2). The reported irradiance of Bluephase N MC was 800 mW/cm², whereas the measured irradiance at 0 mm was 1,313 mW/cm², being 64% greater, while that at 5 mm was 13% greater. When Bluephase N was used in low power mode, the measured irradiance was 813 and 605 mW/cm² at 0 and 5 mm respectively, corresponding to 25% more than the manufacturer's stated irradiance, whereas that at 5 mm was <7%. The manufacturer's reported irradiance for Nano was >1,500 mW/cm², whereas the lamp produced 18% more irradiance at 0 mm; at 5 mm, it showed the greatest loss of irradiance at 34%, corresponding to 995 mW/cm². When VALO was used in standard power mode, the measured irradiance was 1,326.7 and 786.6 mW/cm² at 0 and 5 mm respectively, corresponding to >33% and <21% of the manufacturer's stated irradiance.

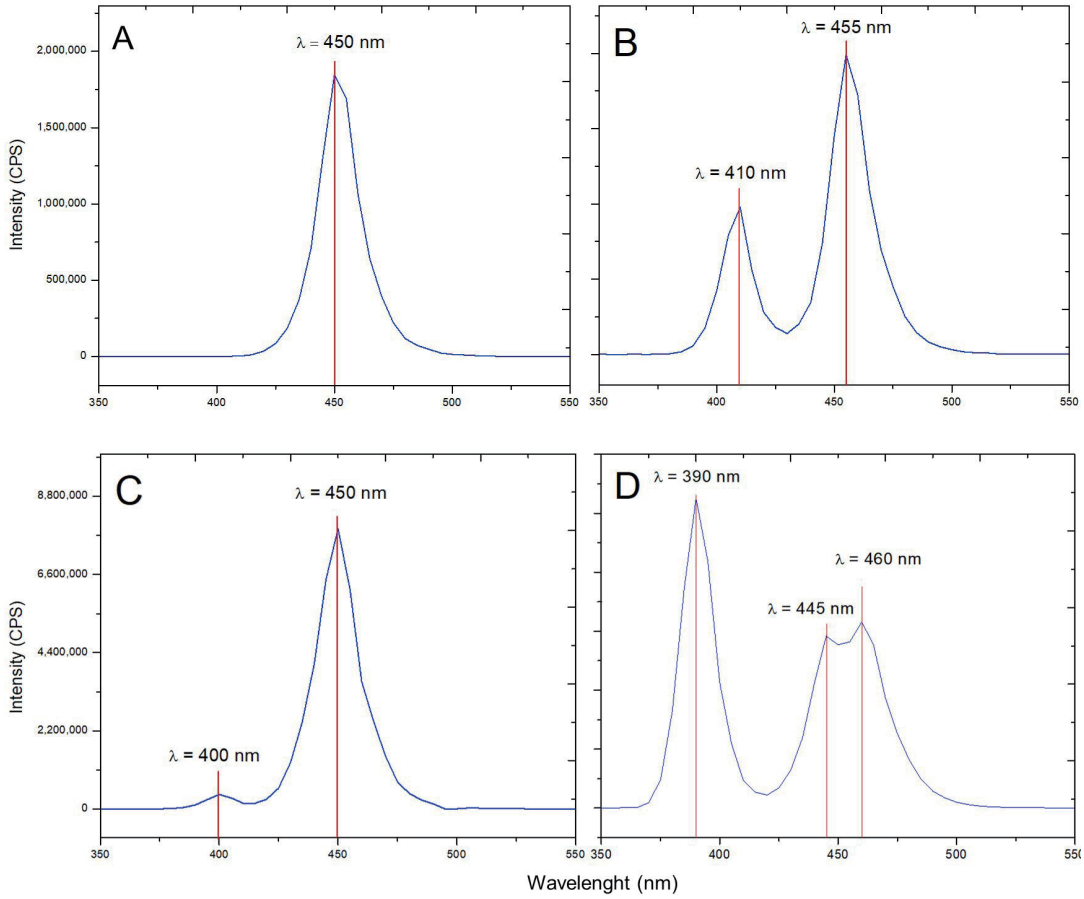

Fig. 1 Wavelength spectra of the four LCUs
A- Bluephase N MC; B- Bluephase N, C- Nano COXO and D- VALO Cordless

Table 2 Measured and manufacturers' reported irradiance values at two polymerization distances

	Bluephase N MC		Bluephase N		Nano COXO		VALO	
Reported irradiance in mW/mm² (RI)	800		650		>1,500		1,000	
Measured irradiance in mW/mm² (MI)	0 mm	5 mm	0 mm	5 mm	0 mm	5 mm	0 mm	5 mm
	1,313.3 (16.0)[a]	906.7 (27.5)[b]	813.3 (43.2)[a]	605.0 (28.7)[b]	1,773.3 (50.0)[a]	995.0 (92.7)[b]	1,326.7 (27.49)[a]	786.6 (47.1)[b]
Median	1,325	900	825	600	1,775	1,000	1,325	775
Interquartile range	25	25	50	50	50	125	50	100
Calculated energy density in J/cm²	26.26 (0.32)[a]	18.12 (0.54)[b]	16.26 (0.86)[a]	12.10 (0.56)[b]	35.46 (1.00)[a]	19.90 (1.84)[b]	26.52 (0.54)[a]	15.72 (0.94)[b]
Median	26.4	18	16.5	12	35.5	20	26.5	15.5
Interquartile range	0.5	0.5	1.0	1.0	1.0	2.0	1.0	2.5
Difference between RI and MI	>64%	>13%	>25%	<7%	>18%	<34%	>33%	<21%
Decrease in irradiance from 0 to 5 mm	31%		26%		44%		40%	

Values are means and standard deviations (shown in parentheses). Different superscript lowercase letters indicate statistically significant differences for each lamp between distances of 0 and 5 mm (Mann-Whitney *U* test, $P < 0.001$) $n = 15$.

Observation of the irradiance behavior of the LCUs at 0 and 5 mm (Fig. 2) showed that Bluephase N MC and VALO had greater homogeneity through the 15 measurements, with an irradiance loss of 31% and 40% at 0 and 5 mm, respectively. Nano COXO showed an irradiance loss of 44% between the two distances, exhibiting heterogeneous behavior during the measurements. Bluephase N showed the lowest irradiance change between the two distances (26% reduction).

Depth of cure, flexural strength, and elastic modulus

The depth of cure at 0 mm was similar from 2.33 to 2.74 mm in all groups, and statistically significant differences were noted between all groups, except for Bluephase N vs. VALO (ANOVA $P < 0.05$, *post hoc* Tukey test $P < 0.05$). The depth of cure decreased with light curing at 5 mm distance, with values of 1.95-2.36 mm, and statistically significant differences were noted between all groups, except for Bluephase N vs. Nano COXO (ANOVA $P < 0.05$, *post hoc* Tukey test $P < 0.05$). Significant differences between LCUs were also found at each distance (paired *t*-test $P < 0.05$), except for Bluephase N, which showed a cure depth of 2.33 and 2.36 mm at 0 and 5 mm, respectively (Table 3).

At 0 mm distance, flexural strength differed significantly only for Bluephase MC, which showed the highest flexural strength (105.55 MPa), vs. VALO, which showed the lowest (79.61 MPa) (ANOVA $P < 0.05$, *post hoc*

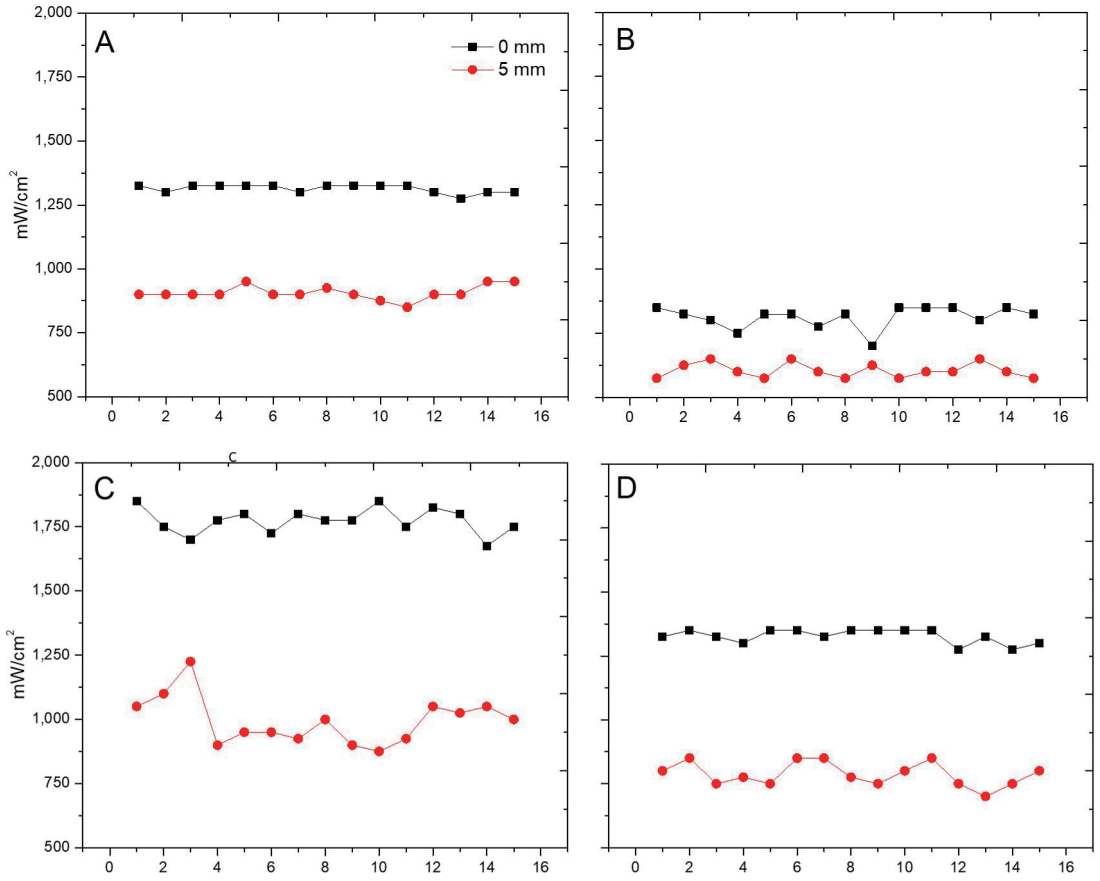

Fig. 2 Irradiance of the LCUs during 15 curing intervals for 20 s, at 0 mm (square black mark) and 5 mm (circle red mark)
A- Bluephase N MC, B- Bluephase N, C- Nano COXO, D- VALO Cordless

Tukey test $P < 0.05$). Flexural strength was affected when the resin composite was light cured at 5 mm distance, the values ranging from 73.68 to 83.82 MPa, although no significant differences were found between groups (ANOVA $P > 0.05$). Comparison of the LCUs at the two distances revealed statistically significant differences for Bluephase MC and Bluephase N (paired *t*-test $P < 0.05$) (Table 3).

In contrast, the elastic modulus showed no statistically significant differences when it was compared for each LCU at the two distances (paired *t*-test $P > 0.05$). VALO showed the lowest elastic modulus at 0 and 5 mm, being 6.7 and 5.5 GPa respectively, in contrast to the highest value of 9.5 GPa for Bluephase MC at 0 mm. In this case, the differences were significant at 0 mm (ANOVA $P > 0.05$), but not significant at 5 mm (ANOVA $P < 0.05$, *post hoc* Tukey test $P < 0.05$) for VALO vs. Bluephase MC and VALO vs. Nano COXO (Table 3).

SEM showed that the surface of the non-polymerized area was similar in all groups, with a heterogeneous structure and some linear marks of the plastic spatula produced during the elimination of non-polymerized RCB (Fig. 3).

Table 3 Depth of cure, flexural strength, and elastic modulus

LCU	0 mm	5 mm	*T*	Paired *t*-test *P*
		depth of cure (mm)		
Bluephase MC	2.74 (0.12)[a]	1.95 (0.06)[a]	18.62	<0.001*
Bluephase N	2.33 (0.06)[b]	2.36 (0.05)[b]	1.21	0.181
Nano COXO	2.56 (0.07)[c]	2.29 (0.08)[b]	7.8	<0.001*
VALO	2.33 (0.13)[b]	2.12 (0.08)[c]	4.3	<0.001*
F	41.16	68.34		
ANOVA, *P*	<0.001	<0.001		
		flexural strength (MPa)		
Bluephase MC	105.55 (14.01)[a]	73.85 (13.34)[a]	5.18	<0.001*
Bluephase N	86.38 (13.33)[a,b]	73.68 (10.26)[a]	2.39	0.028*
Nano COXO	90.77 (24.30)[a,b]	83.82 (13.76)[a]	0.79	0.441
VALO	79.61 (11.76)[b]	74.63 (10.23)[a]	1.01	0.326
F	4.38	1.66		
ANOVA, *P*	0.01	0.192		
		elastic modulus (GPa)		
Bluephase MC	7.6 (3.8)[a]	9.6 (2.5)[a]	1.19	0.256
Bluephase N	9.5 (3.4)[a]	7.8 (1.1)[a,b]	1.35	0.198
Nano COXO	7.6 (3.6)[a]	8.6 (2.8)[a]	0.64	0.53
VALO	6.7 (1.2)[a]	5.5 (1.5)[b]	1.23	0.202
F	1.37	6.94		
ANOVA, *P*	0.265	<0.001		

Values are mean and standard deviation (in parentheses). Asterisk in each column is used to compare means between the distance of each LCU (paired *t*-test $P < 0.05$). Lowercase superscript letters are used to compare means between the four LCUs in each column, means sharing a superscript letter are not significantly different (ANOVA $P < 0.05$, *post hoc* Tukey test $P < 0.05$), $n = 10$ for LCU, distance and property.

Discussion

This study evaluated the influence of the polymerization distance of monowave and polywave LCUs on the measured irradiance compared to the manufacturer's stated irradiance and the physical properties of RBCs. LCU units are widely used in dentistry because most restorative dental materials require dual or light polymerization. It has been observed that to achieve good polymerization, some factors associated with the RBC need to be considered, such as color [14], photoinitiator [6], and filler particles [12]. However, if the light does not penetrate completely into the resin composite, the depth of cure is reduced, thus affecting the grade of conversion [20-22].

When the first RBCs were introduced, the main photoinitiator was camphorquinone (CQ), which has a marked yellowish color with an absorption peak at 468 nm. However, due to patients' esthetic requirements, new photoinitiators with a lighter and higher color value have been incorporated. Recently, 1-phenyl-1,2-propanedione (PPD), lucerine and trimethylbenzoyl-diphenylphosphine oxide (TPO) have been used as co-initiators for CQ [6], both having an absorption peak of 400-410 nm. Currently a new photopolymerization technology, radical amplified photopolymerization (RAP), has been introduced, which reportedly reduces the amount of CQ and achieves polymerization within a shorter time [7]. However, the exact

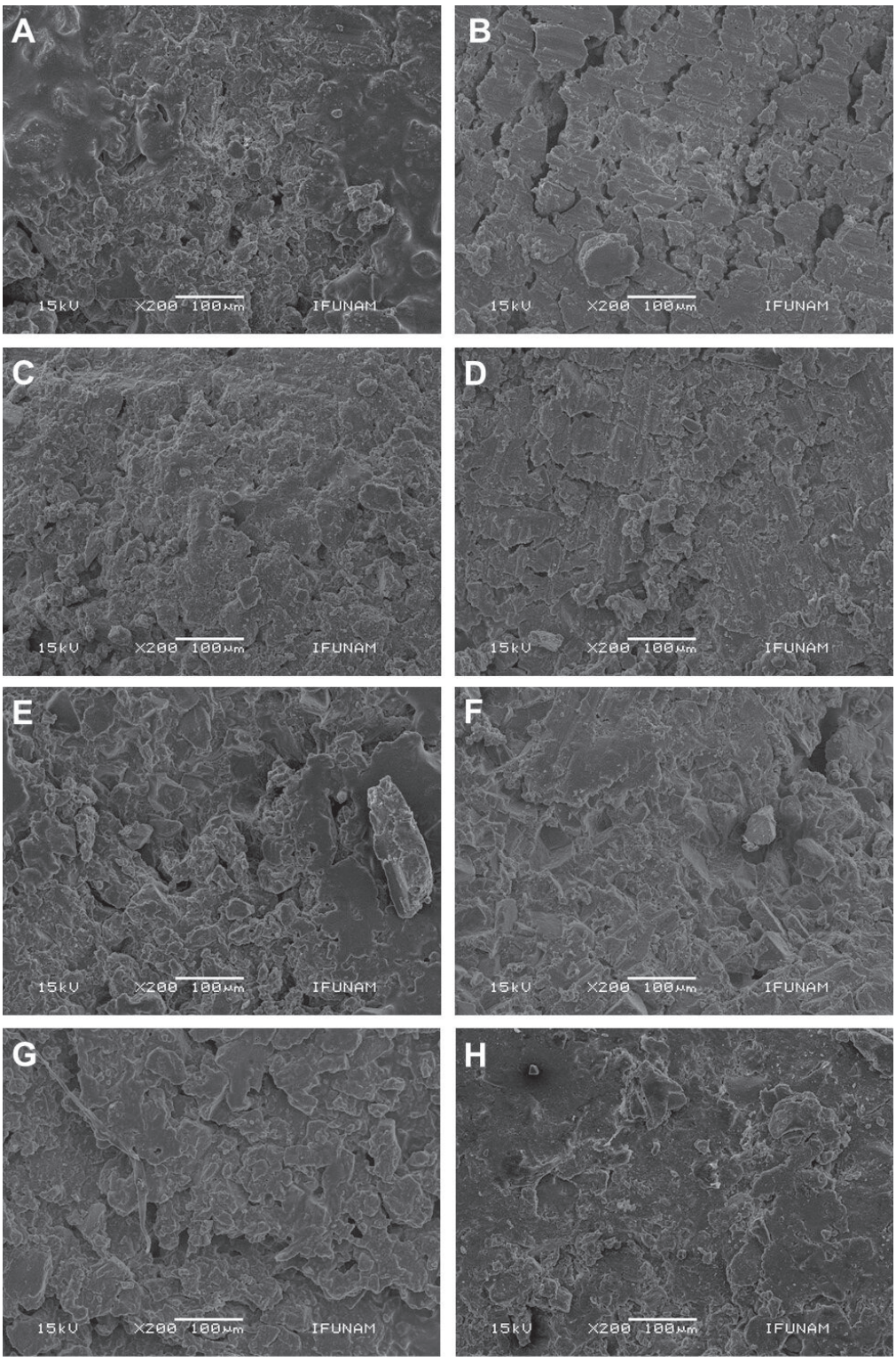

Fig. 3 SEM images obtained with backscattered electrons showing the bottom surface (non-polymerized)
A-B: Bluephase N MC; C-D: Bluephase N, E-F: Nano COXO and G-H: VALO Cordless. Left column (A, C, E, G) corresponding to 0 mm, right column (B, D, F, G) corresponding to 5 mm distance. White scale bars = 100 µm, images were taken at ×200

mechanism is still unknown.

In this sense, LCU characteristics have been modified to improve the polymerization process. LED LCUs initially used a single peak blue light with a range of 450-470 nm, known as a monowave or single-peak, capable of activating the CQ. However, it was necessary to incorporate ultraviolet light LEDs to activate PPD or TPO; therefore, polywave or multipeak LCUs have emerged, using 3-4 LEDs in both the blue and ultraviolet wavelength ranges [23,24]. In this study it was observed that Bluephase N MC presented a single blue light-emitting peak; Bluephase N and Nano showed two emission peaks, one corresponding to ultraviolet light at 400 and 410 nm, respectively and the second one corresponding to blue light at 450 and 455 nm, respectively; VALO, a polywave lamp, showed an emission spectrum with three peaks at 390, 445, and 460 nm. It is known that the emission spectrum does not change with time, even when the irradiance in the different power modes changes [25].

Most manufacturers have reported that the irradiance of LCUs can show 10-15% variation. In this study, the measured irradiance of the four LCUs at 0 mm was higher than the reported value, being 18% more for Nano COXO and up to 64% for Bluephase N MC. In contrast, at 5 mm, whereas Nano COXO showed an irradiance reduction of 34%, VALO

showed 21% less irradiance whereas Bluephase N MC still showed a value 13% higher than the reported one. Accordingly, it is crucial to consider that a minimum energy density of 16 J/cm^2 is needed to achieve correct RBC polymerization [26], and so the irradiance (mW/cm^2) and time should be adjusted appropriately, in this case, just two LCUs do no accomplish with this value of J/cm^2, corresponding to previous reports [27].

In this study the irradiance decreased from 26% to 44% when the tip of the LCU was positioned 5 mm away from the RBC. The main reason is that the light produced by the LCU is not coherent, and consequently the photons are dispersed into the environment in accordance with the inverse square law, i.e. "irradiance is inversely proportional to the distance squared from the source of radiation" [Brownson JRS., Laws of Light. Solar Energy Conversion Systems. Chapter 3: 41-66, 2014]. Therefore, when a deep cavity preparation is performed (more than 5 mm deep) a LCU with a higher irradiance is recommended to ensure polymerization, as the LCU tip is located further away from the RBC surface. It is also expected that a higher irradiance would lead to an increase in temperature. It has been reported that when an energy of 500 mW/cm^2 is used to polymerize a 1.4-mm-thick RBC at 5 mm distance, the temperature rises to 27-28.5°C, whereas for 1,000 mW/cm^2 and 1,500 mW/cm^2, the temperature rises to 39°C and 42-47°C, respectively [28]. The increase in temperature is linear while the light is activated, and the temperature in the pulp chamber measured 10 s after light exposure has been reported to range between 5.5 and 11.2°C [29], but values of 39-42°C have also been reported [30,31] depending on the RBC thickness, leading to a possible cell death.

There are many factors involved in this process: cavity depth, dentin thickness, RBC thickness, RBC filling volume [12], irradiance, and the length of exposure to the curing light [28,30-33]. For a low-irradiance LCU it takes a longer time than a high-irradiance LCU to deliver the same radiant exposure (J/cm^2) to a restoration, and in clinical practice an exposure time of 20 s is considered adequate, without considering the energy density or the irradiance. Interestingly, the present study showed that irradiance was related to the connection type of the LCU. Bluephase N MC and VALO, which are wired LCUs, showed greater homogeneity during 15 continuous measurements at 0 and 5 mm, unlike the behavior of the two wireless LCUs. The changes in intensity among the 15 measurements were not statistically significant, although it has been reported that for wireless LCUs that are fully charged, up to 50 continuous measurements are needed to reduce the irradiance [34].

For conventional RBC, 2-mm increments of resin composite have been recommended, and the manufacturer usually indicates the appropriate irradiance and exposure time needed to achieve correct polymerization. It was observed that the depth of cure was affected by the polymerization distance, being reduced from 2.74 mm to 1.95 mm at 5 mm for Bluephase MC. However, although Bluephase N showed the lowest difference in irradiance at the two distances (25%), there were no differences in this property, i.e. 2.33 mm and 2.26 mm at 0 mm and 5 mm, respectively. Contrary to other LCUs where the irradiance was reduced by 31-44%, it was found that there were significant differences in the depth of cure at distances of 0 mm and 5 mm. Furthermore, all of the LCUs showed significant differences from each other at both 0 and 5 mm. Among the four LCUs used in this study, monowave LCU and Bluephase MC showed the deepest cure at 0 mm, 2.74 mm, and the irradiance was similar to that of VALO, i.e. 1,313 and 1,326 mW/cm^2, respectively, whereas the latter had a 2.33-mm depth of cure. These differences could be related to the homogeneity of the beam light; monowave LCU exhibited a unique wavelength peak, indicating a homogeneous beam light concentration, but the presence of 3-4 LEDs in polywave LCUs has been reported to concentrate 3 or 4 light beams in different areas [8], thus possibly leading to insufficient illumination during polymerization or an inadequate wave form. As the maximum depth of cure in the present study was 1.95-2.36 mm, sufficient mechanical properties might be achieved if 2-mm thickness increments are created during clinical treatment. Thus according to ISO 4049, for materials classified as type 1, class 2-group I, the depth of cure must be at least 1.00 mm for body (dentin) RBC and 1.5 mm for translucent RBC.

These results are consistent with previous research, where the depth of cure was affected by the distance of the LCU tip [35]. In deep cavities where the light source from the RBC is further and the irradiance is reduced, it is important to increase the exposure time [36], and it was found that, at the same irradiance, with exposure times ranging from 10 to 20 s, the depth of cure was improved by up to 1 mm. Therefore, some micro properties such as microhardness, degree of conversion and wear resistance can also be affected [37-39], possibly leading to pigmentation, deficient marginal adaptation and sorption.

A variety of forces are exerted on the oral cavity during the chewing process, and bite force values of 480-640 N have been reported [40]. RBC and other restoration materials must withstand such forces, and in the present study flexural strength showed no differences after polymerization at 0 or 5 mm for polywave LCU Nano COXO (90.77 MPa and 83.82 MPa, respectively) and VALO (79.61 MPa and 74.63 MPa, respectively). In contrast, a significant decrease from 105.55 MPa to 73.85 MPa was observed for Bluephase MC, and for Bluephase N the flexural strength of 86.38 MPa at 0 mm was reduced to 73.68 MPa at 5 mm. According to ISO 4049, the sample thickness for this test is 2 mm and polymerization of the sample is performed in an overlapping manner on both the top and bottom sides. This ensures sample polymerization through overexposure to irradiation. This standard stablished a minimum flexural strength of 80 MPa, and this minimum value was achieved for the four LCUs when polymerization was performed at 0 mm distance. However, when the distance was increased, the flexural strength was below 80 MPa, except for Nano COXO. The elastic modulus does not seem to be affected by polymerization distance, since it showed no significant differences at distances of 0 and 5 mm for any LCU. It also showed no significant differences among the LCUs at 0 mm, suggesting that it is not affected by irradiance or distance.

Polymerization is a complex process in which factors related to the RBC need to be considered, such as filler content, photoinitiator, shade and opacity, although LCU-related factors are also important. Parameters such as irradiance, energy density, exposure time, and wavelength spectra are essential for achieving optimal resin polymerization. In this way, dentists manage to compensate for certain shortcomings. For example, if the distance cannot be 0 mm, such as in a deep cavity, the exposure time should be increased to achieve the 16 J/cm^2 energy necessary for breaking the C=C bond. Degree of conversion and microhardness should be implemented to analyze the chemical and surface changes related to the double bond.

Within the limitations of this study, it can be concluded that LCUs are an important device for dental practitioners, who must be aware of their specific characteristics. Concepts like irradiance and energy density must be well understood. The LCU must be placed as close as possible to the RBC restoration during polymerization, and any increase of the distance has an adverse effect on some macro properties such as depth of cure and flexural strength.

Abbreviations

ANOVA: analysis of variance; Bis-EMA: ethoxylated bisphenol A-glycol dimethacrylate, Bis-GMA: bisphenol A-glycidyl methacrylate, CQ: camphorquinone, DC: depth of cure, FS: flexural strength, HEMA: hydroxyethyl methacrylate, LCU: light curing unit, LED: light emitting diode, PPD: 1-phenyl-1,2-propanedione, RBC: resin-based composite, SEM: scanning electron microscope, TEGDMA: triethylene glycol dimethacrylate, TPO: trimethylbenzoyl-diphenylphosphine oxide, UDMA: urethane dimethacrylate

Ethical Statements

Not applicable

Conflicts of Interest

The authors declare that they have no conflicts of interest related to the present study.

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Author Contributions

RPM: investigation, writing - original draft; MBMA: project administration, writing - review and editing, validation; SVJA: resources, writing - original draft; ROJP: resources, methodology; SRLE: resources, investigation; RCJA: project administration, writing - review and editing, supervision; FLA: conceptualization, formal analysis, writing - original draft, writing - review and editing, supervision, visualization

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Data Availability Statements

Data are available on request.

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