Ability of Six Curing Lights to Photocure Four Resin-Based Composites in a MOD-Mold: A Double-Blind Study

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ABSTRACT

Objective: The ability of six curing lights to photocure four resin-based composites (RBCs) in a mold simulating a cavity was compared visually. Materials and Methods: Four RBCs were photocured using the: Woodpecker B for 2x10s, SmartLite Pro 2x10s, Valo Cordless 2x10s, Valo Cordless 2x3s Xtra power, Valo X 2x10s, Valo X 2x5s Xtra power, PowerCure 2x3s mode, Monet 1x1s and Monet 3x1s, in a mold representing a molar Class II restoration. Immediately after photocuring, the RBC specimens were immersed in a solvent to remove the uncured RBC, after which they were photographed and de-identified. Using a REDCap survey, these images were compared visually to compare the ability of the LCUs to photocure the restorations. Results: There were significant differences in how well the LCUs had photocured the RBCs. The SmartLite Pro and Valo X used for two 10s exposures produced restorations rated as the best cured, and the Monet used for 1 s was rated the worst. Conclusions: There were visually apparent differences in how well the LCUs could photocure the RBCs. The Monet used for 1 second produced the worst results for all four RBCs.

INTRODUCTION

According to the World Health Organization (WHO), dental caries has become the most widespread non-communicable global disease.[1] Based on WHO data, it has been estimated that the annual global economic burden of dental caries is approximately $245 billion, of which $161 billion is in direct treatment costs and $84 billion is in indirect losses.[2-4] Thus, treating dental caries now accounts for the third-highest global expenditure among non-communicable diseases.[5] Due to the esthetic demands of patients and the Minamata agreement to phase down the use of amalgam,[6,7] there has been a dramatic move away from placing dental amalgam restorations to now using photocured resin-based composites (RBCs). With the additional planned ban on using and exporting dental amalgam in the European Union starting 1 January 2025,[8] the use of RBCs will be further accelerated. Most resin-based restorations will be transformed from uncured dental resin into hard, highly cross-linked restoration using a dental light curing unit (LCU).[9,10] Thus, the light curing unit (LCU) and how it is used has become an essential part of a dental practice.

The two most common reasons for replacing RBC restorations are fractures of the RBC and secondary dental caries,[11-14] and it has been estimated that replacing failed restorations accounts for more than half (57%) of the restorations placed by dental practitioners.[15] Resin manufacturers and researchers

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know that when an insufficient amount of energy is delivered to the RBC, or if the light is at the wrong wavelength, this can produce an undercured resin restoration.[9,10,16-21] Consequently, to achieve good results, researchers will usually fix the LCU directly over the specimen at a distance of 0 mm and deliver more than the minimum amount of light recommended by the resin manufacturer to achieve the best results.[22]

Most studies that evaluate the ability of LCUs to photocure RBC only evaluate the RBC at the center of the specimens directly under the center of the light,[23-26] and the ISO 4049 standard 'Dentistry Polymer-based filling, restorative materials'[27] only determines the maximum length of hard RBC. For this test, a metal mold that has a 4 mm in diameter hole is filled with RBC. The RBC is then exposed to one light exposure from the top surface, and immediately after photocuring, the RBC is removed from the metal mold. Then, the uncured or only partially cured material is immediately scraped away with a plastic instrument. The maximum length of the remaining cylinder of hard RBC is measured, and the ISO depth of cure is determined by dividing this maximum length by 2. However, the ISO 4049 test has some limitations.[28-30] The depth of cure is known to be less when the specimens are made in a 4-mm diameter stainless-steel mold when compared with the results from a 6-mm-diameter stainless-steel or in a semi-opaque mold,[29-32] and the shape of the RBC at the end is often rounded, or 'bullet-shaped' with the maximum length at the center.[30,33] Molar teeth often receive restorations that are greater than 4 mm in diameter. For example, on average, the mandibular first molar tooth is 11.0 mm in mesio-distal length and 10.5 mm in bucco-lingual width.[34] These teeth will often receive mesial-occlusal-distal (MOD) restorations that are larger than 4 mm in diameter. The RBC in the ISO 4049 test can receive no light from the sides due to the opaque nature of the metal mold, and the effects of distance from the light tip, the angle of the light tip, or the irradiance beam profile from the LCU are not tested.[19,32,33,35-38] Thus, the 4 mm diameter mold used in the ISO 4049 test[27] does not represent clinical reality. A few studies have examined how well the LCU can photocure specimens that better represent the size of a restoration in a molar tooth. These studies have reported that while the RBC at the center is well cured, the RBC at the sides or at the bottom of the proximal boxes is more difficult to photocure.[35,36,39] While some additional polymerization can occur if the RBC receives trans-tooth light at the end of the restorative procedure, as the thickness increases, there is an exponential decline in the amount of light transmitted through both the tooth and the RBC.[40-43] Thus, deficits in polymerization are challenging to compensate for at the end of the restorative process.[20,43-45]

For ethical reasons, it remains to be proven that a poor bond strength or an inadequately polymerized RBC will cause premature failure of the restoration. However, there is substantial *in-vitro* laboratory research showing that delivering an insufficient radiant exposure will reduce the bond strengths of RBCs to teeth, negatively affect the physical properties of RBCs, and increase the cariogenic plaque retention at the gingival margins of extensive class II RBC restorations.[16,17,39,46-56] In addition, if the RBC does not reach a sufficient degree of monomer conversion, it is more likely to leach undesirable substances into the mouth.[18,57-60] Of note, a recent clinical trial reported that increasing the exposure time for the adhesive from 10 to 40 seconds, thus delivering more energy, improved the clinical longevity of non-carious cervical restorations after 36 months of clinical service.[54] Another report illustrated how some LCUs failed to photo-cure the RBC at the bottom of some restorations.[39] Consequently, most dentists know that they need a good LCU,[21] and dentists rank high irradiance as the #2 feature (after portability) when choosing which LCU to purchase. [21] However, most dentists[61-65] and even researchers[22] do not recognize the importance of the wavelengths of light emitted from the LCU, light and energy beam profiles, or the radiant exposure they deliver when light-curing resins in the mouth.

Dentists want to shorten the time spent on each dental appointment because it allows more restorations to be placed and photocured in the same amount of time, thus generating more revenue.[66] It has even been calculated that if five seconds of light exposure was used instead of 30 seconds to cure 2200 restorations under the same conditions, a dentist could save enough time to generate US$26,399 more annually.[67] Time can also be saved by using bulk-fill RBCs,[68-71] thus reducing the number of light exposures.

Currently, almost all LCUs use LEDs as the light source, but the newest curing light technology[72] uses a solid-state laser diode (LD) emitter. In 2021, the manufacturer of this LD curing light claimed it could photopolymerize 2 mm of resin composite using only a 1-s exposure, thus saving chairside time.[72] For RBCs increments thicker than 5 mm, they now (2024) recommend using three exposures, each lasting one second.[72] Some publications have already reported that using this laser diode LCU for 1 s did not photocure RBCs as well as LED lights that were used for 10 seconds.[39,55,56,73] This may occur because the Monet LD does not deliver the same amount of energy to the RBC in one second as many conventional LED curing lights in 10 seconds, and the beam profile is narrower than the full diameter of the light tip.[55,56,73] This requires further investigation. In addition, LD curing lights deliver a very narrow wavelength range with a full-width half maximum (FWHM) value of only about 2 nm, whereas blue light LEDs have an FWHM of about 22 nm.[55,56,73] While it has been reported that if sufficient radiant exposure is delivered (>22 J/cm^2), then a laser LCU with a peak emission at 445 nm can achieve as good if not a higher degree of conversion at the center of some RBC specimens compared to LED-based curing lights,[26,74,75] the narrow beam width of the Monet does not cover a molar tooth-sized MOD restoration, thus necessitating multiple exposures.

As described previously, the ISO 4049 test method scrapes away the uncured RBC from a 4 mm diameter cylinder using a plastic instrument immediately after photo-curing and measuring the maximum length of hard RBC remaining after scraping.[27] This method is unsuitable for measuring the depth of cure in a mesial occlusal distal (MOD) restoration. The test requires a trained operator to apply the same scraping force to all the specimens and a cylinder. An alternative method uses a no-touch solvent dissolution method to remove the uncured resin, and then the remaining amount of hard RBC determines the depth of cure. In 2004,[76] it was suggested that this solvent dissolution method may be more reliable and less prone to operator-induced variables than the scraping method specified in the ISO 4049 standard,[27] and it has been used in several publications since then.[30,39,77-79]

To introduce some relevance and provide a visual demonstration of how well the LCU can photocure the RBC, the same tooth mold used in a previous study[39] was used to investigate the ability of six brands of LCU to photocure four different brands of RBC. This mold was made of semi-transparent Delrin to represent a mandibular first molar that had an extensive mesial occlusal distal (MOD) preparation.[39] The hypotheses were that:

1. The emission spectra, power, irradiance values and beam profiles from these 6 LCUs will be uniform and similar.
2. Similar radiant exposures will be delivered from the LCUs to the RBCs.
3. The LCUs and different exposure times will produce RBCs that have visibly similar resistance patterns to solvent dissolution.

METHODS

The six brands of LCU, the nine exposure modes, and the four brands of paste consistency universal RBCs together with their recommended exposure times and radiant exposures used in this study are reported in Tables 1 and 2. Images of the 6 LCUs are shown in Figure 1. One of the LCUs was a laser diode LCU (Monet).

Using previously described techniques,[80,81] the radiant power and the emission spectra of the LCUs were measured through a 16 mm aperture into a six-inch integrating sphere (LabSphere, North Sutton, NH, USA) that was connected to a fibre-optic spectrometer (USB 4000, Ocean Insight, Orlando, FL, USA). The tip of the LCU was positioned 0 mm away from and parallel to the entrance into the sphere. In addition, the light beam profiles from each LCU were measured using a laser beam profiler (SP620U, Ophir-Spiricon, Logan, UT, USA). The LCU guide tip was placed against one side of a 60-degree holographic diffusing screen (#54-505 Edmund Optics, Barrington, NJ, USA) and viewed from the other side of the screen using a digital camera (USB-L070, Ophir-Spiricon). The internal diameter of each light tip was measured with a digital caliper (Mitutoyo, Kawasaki, Japan) and used to produce scaled color-coded images using BeamGage Professional 6.14 software (Ophir-Spiricon) where red represents high (100% or maximum irradiance). The colour purple represents a low irradiance and red represents the highest irradiance at the emitting tip of the light guide.

A total of 108 samples of the RBCs were prepared, three for each combination of each LCU and RBC (9 exposure conditions X 4 RBCs X 3 repetitions). Since two of the manufacturers

Table 1. Resin Based Composites (RBCs), manufacturer, lot number, shade, maximum recommended increment (mm), minimum irradiance (mW/cm²), minimum exposure time, and calculated minimum radiant exposure (J/cm²) based on the manufacturer's instructions for use.

RBC Brand	Company	Lot	Shade	Maximum Recommended Increment Thickness (mm)	Minimum Irradiance LED LCU (mW/cm²)	Minimum Exposure Time (s)	Minimum Radiant Exposure (J/cm²)
Filtek Universal Restorative	3M, St. Paul MN, USA	NE15442	A2	2mm	1000	One 10 s from the occlusal	10
Omnichroma	Tokuyama Dental Corporation, Encinitas, CA, USA	042E41	Universal	2.5 to 3.6 mm depending on the irradiance and exposure time	400	6 to 40 s depending on the irradiance	8
SimpliShade Universal	Kerr Corporation, Orange, CA, USA	8086055	DK	2 mm	1000	One 6 to 40 s exposure from the occlusal depending on the irradiance	10
Transcend	Ultradent Products Inc. S. Jordan, Utah, USA	RN776	UB	2 mm	800	10 s with an additional 20 s exposure at the end	8

Table 2. Light Curing Units, type, nine exposure modes, exposure times, and claimed irradiance.

Light Curing Unit and abbreviation	Serial Number	Manufacturer	Type	Wavelength (nm)	Exposure time and Mode	Claimed Irradiance (mW/cm²)
Woodpecker LED B (WP)	L12B0572B	Guilin Woodpecker Medical Instrument Co., Guilin, Guangxi, China	Single peak wavelength LED	420 - 480	2x10 s (Standard)	850 - 1,000
Bluephase PowerCure (PC)	1428005297	Ivoclar Vivadent, Schaan, Liechtenstein	Multiple peak wavelength LED	385 - 515	2x3 s (3s mode)	3,050 (± 10%)
SmartLite Pro (SLP) 2x10 s	H00466	Dentsply Sirona, Charlotte, NC, USA	Single peak wavelength LED	450 - 480	2x10 s (Standard)	1,200
Valo Cordless (VC)	C43122	Ultradent, South Jordan, UT, USA	Multiple peak wavelength LED	385 - 515	2x10 s (Standard) and 2x3 s (Xtra power)	900 (± 10 %) 2,100 (± 10%)
Valo X (VX)	C43122	Ultradent, South Jordan, UT, USA	Multiple peak wavelength LED	380 - 515	2x10 s (Standard) and 2x5 s (Xtra power)	1,100 (± 10 %) 2,200 (± 10%)
Monet (M)	00249	AMD Lasers, West Jordan, UT, USA	Single peak wavelength Laser diode	450 ± 5	1x1 s and 1x3 s	2,000 - 2,400

Figure 1: The six LCUs used in this study.

(3M and Kerr) specifically state in their instructions for use that the recommended light exposure is a single exposure from the occlusal surface, the ISO 4049 standard uses only one exposure, and the report that some dentists only use one light exposure when light curing a posterior restoration,[82] all the RBCs were exposed from the central location only. Each RBC was photocured under ideal conditions at a distance of 0 mm in a semi-transparent Delrin mold[39] that represented the dimensions of a mesial-occlusal-distal (MOD) Class II restoration in a mandibular first molar tooth.[34,83,84] The mold was 5 mm wide bucco-lingually, the central region was 5 mm deep, the proximal boxes were 7 mm deep, and the mesial-distal length was 12 mm. After the mold had been filled with the RBC, the LCU light tips were fixed in position over the center of the mold containing the RBC. The LCU was then turned on for the specified exposure time and the RBC was photo-cured (*Table 2*). Immediately after photocuring, the RBC restorations were removed from the mold and coded. They were then immersed in 2-butanone (Sigma-Aldrich, San Luis, MO, USA) to dissolve the uncured RBC. After one hour, the specimens were removed, and when dry, they were placed in a methylene blue stain for one hour just to enhance the visibility of any porosities. The RBC samples were then removed, washed, dried, and photographed under standardized lighting conditions.

The amount of RBC remaining provided a visual indication of where the RBC had been photo-cured and was resistant to solvent dissolution.

The images of 108 samples of RBCs were evaluated using a blinded REDCap survey. Twenty-one evaluators were calibrated and then asked to rank each photograph subjectively. The images of the RBCs were ranked from 1 to 5 to estimate how well the RBC was cured, where 1 represented a poor cure, and 5 represented a very good cure. The survey responses were normalized and analyzed using One Way ANOVA, Pairwise T-Test, and Shapiro-Wilk Normality Test, followed by Welch's One Way ANOVA and Kruskal-Wallis Rank Sum Test to determine if there were any significant differences between the ability of the LCUs to photo-cure the RBCs.

RESULTS

Table 3 shows that the internal light tip diameters of the LCUs ranged from 7.0 to 12.6 mm, and there was thus a threefold difference in the area of the light tips, 38.5 mm^2 up to 124.7 mm^2. The Valo X on the Xtra power setting emitted the greatest power (2,575 mW), and the Woodpecker B (a budget LCU) was the least powerful LCU (348 mW). When used for 20s, the SmartLite Pro delivered the greatest radiant exposure (22.6 J/cm^2), and the Monet used for 1 second delivered the lowest (1.4 J/cm^2).

The spectral radiant powers from the 6 LCUs differed notably (*Figure 2*). The Woodpecker B, SmartLite Pro and Monet were all single-peak emission LCUs, whereas the Bluephase PowerCure, Valo and Valo X were multiple-peak broadband LCUs. The Monet was a laser that emitted a narrow bandwidth single peak emission at 451 nm of blue light. Although Figure 2 shows that all the LCUs emitted blue light, Table 3 and Figure 2 show that only the PowerCure, Valo and Valo X emitted any violet light (<425 nm), with the Valo X on the Xtra power setting delivering the most amount of light <425 nm (675mW) and the Bluephase PowerCure the least amount of violet light <425 nm (154 mW). The other three LCUs delivered no light below 425 nm.

Figure 3 provides the scaled irradiance beam profiles of the curing lights superimposed over the 12-mm long MOD mold. These images illustrate the differences in the light tip diameter and the resulting coverage over the MOD restoration. The irradiance beam profiles of the Woodpecker B and the Monet had 'hot spots' of high irradiance at the center of the light tip, and the irradiance distribution from these two lights was less uniform than from the other four LCUs.

Since the exposure times used differed, the radiant exposures (irradiance x exposure time) delivered from the LCUs for the exposure times used in this study were calculated and used to produce Figure 4. These images were superimposed over the MOD mold used in the study, and they show that the center of this mold received a 'hot spot' of high energy from the Woodpecker B and the PowerCure, whereas the sides of the metal mold received no direct light energy from these LCUs. In contrast, the entire mold was covered by light from the SmartLite Pro, Valo X, and the Monet. Still, the energy delivered by the Monet in 1 s beyond the center of the MOD restoration was less from the Monet (more dark purple indicating a low radiant exposure) than from the SmartLite Pro and the Valo X (more yellow and green indicating a higher radiant exposure > 20 J/cm^2).

Table 3. Power (mW), tip diameter, irradiance (mW/cm^2), radiant exposure (J/cm^2), and power (mW) emitted above and below 425 nm.

LCU and Mode	Internal Tip Diameter (mm)	Internal Tip Area (mm^2)	Power (mW)	Irradiance (mW/cm^2)	Time (s)	Radiant Exposure (J/cm^2)	Power (mW) < 425 nm	Power (mW) > 425 nm
Woodpecker B	7	38.5	348	905	20	18.1	0	348
SmartLite Pro	10	78.6	888	1130	20	22.6	0	888
PowerCure-3s mode	8	50.3	1526	3035	6	18.2	92	1433
Valo - Standard	9.5	70.9	707	998	20	20.0	154	553
Valo - Xtra power	9.5	70.9	1640	2314	6	13.9	376	1264
Valo X - Standard	12.5	122.7	1278	1041	20	20.8	339	939
Valo X – Xtra power	12.5	122.7	2575	2098	10	21. 0	675	1900
Monet - 1 s	12.6	124.7	1773	1422	1	1.4	0	1773
Monet - 3 s	12.6	124.7	1773	1422	3	4.3	0	1773

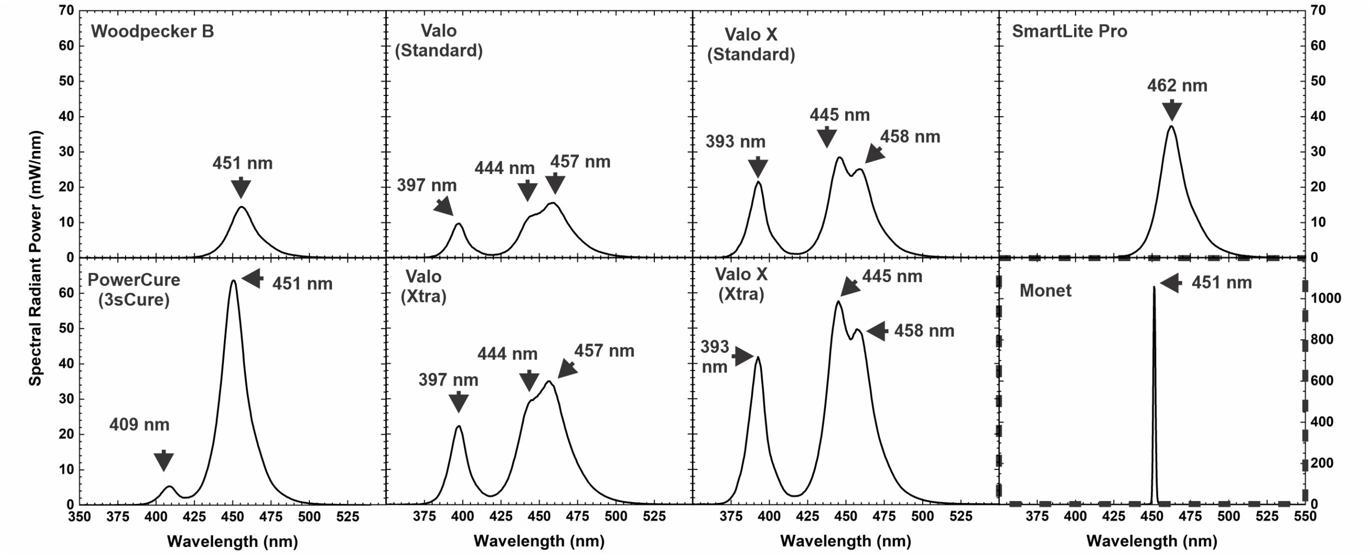

Figure 2: Spectral radiant powers from the six LCUs.

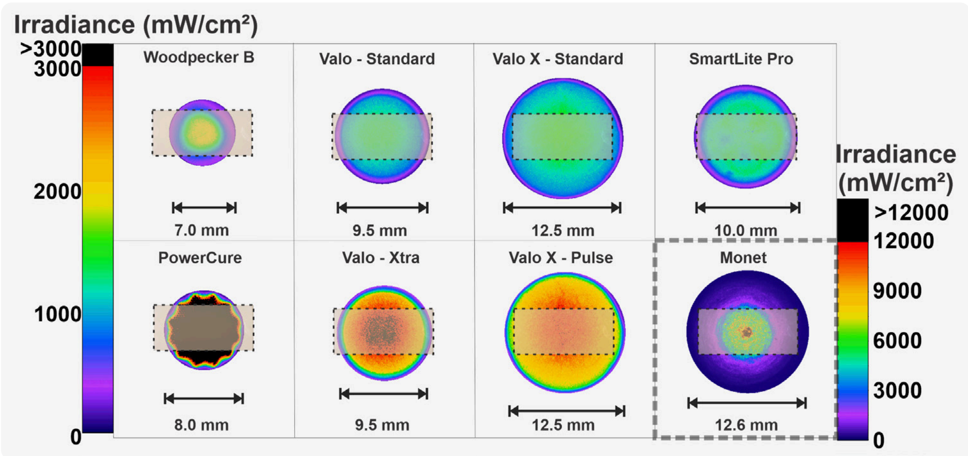

Figure 3: Scaled irradiance beam profiles from the LCUs. Note that the irradiance scale is different for the Monet laser (up to 12,000 mW/cm²).

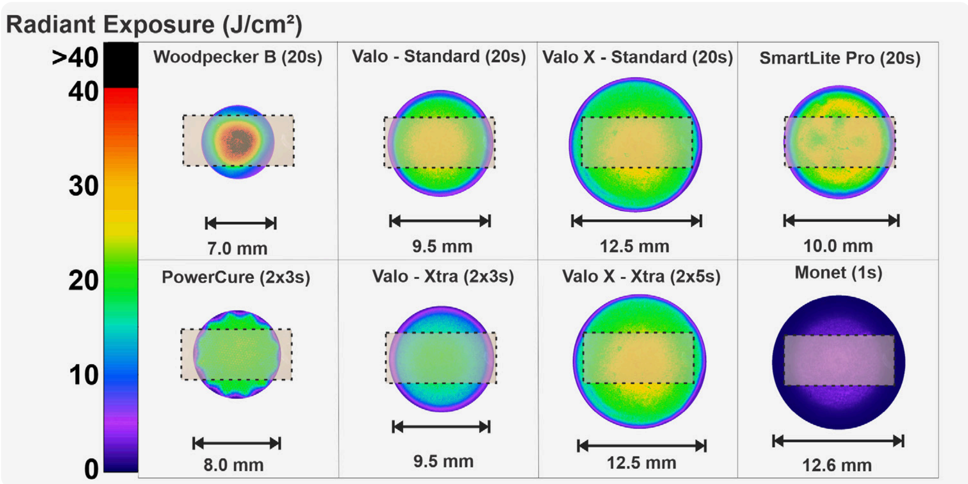

Figure 4: Scaled radiant exposure profiles from the LCUs. Only the SmartLite Pro, Valo X and Monet LCUs covered the RBC in the mold with direct light from the tip of the LCU.

The survey averages were ranked from best to what the evaluators thought were the least to the best cured responses. The Shapiro-Wilk normality test results confirmed that the data was normally distributed (p=0.092). Figure 5 shows that the data met homoscedasticity and normal assumptions of linear regression.

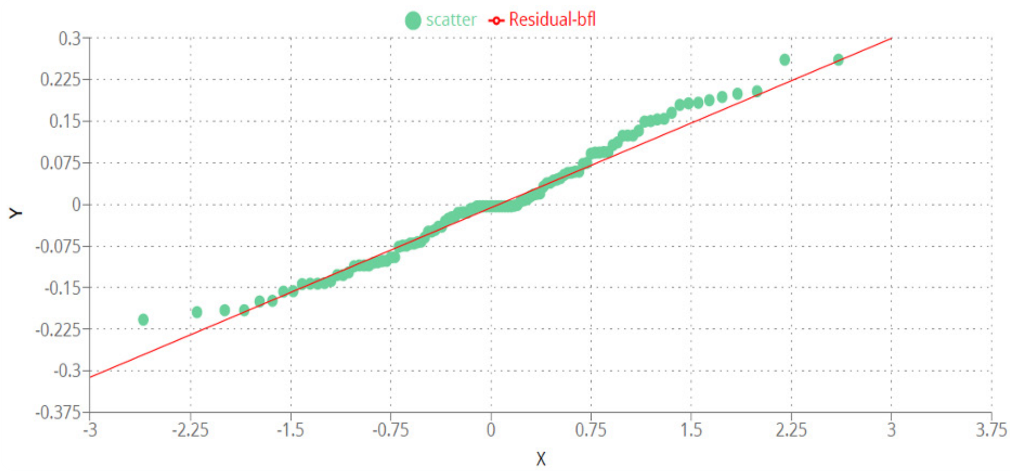

Figure 5: Normal Q-Q plot (residual). The data meets homoscedasticity and normal assumptions of linear regression.

There were pronounced visual differences between the RBC specimens. The ten samples of RBC that were ranked to be the best cured are reported in Table 4 in descending order, and the images are shown in Figure 6. Based on the respondent evaluations of the images, the highest-ranking samples were all obtained when the LCU was used for 2 x 10-second exposures, except for the Valo X, when it was used for two Xtra power exposures on Omnichroma (ranked #10).

The ten lowest-ranked scores are reported in Table 5. Every brand of RBC that received a 1 s exposure from the Monet received a score of 1 *(Figure 7)*. Of note, the top surfaces that the dentist could evaluate with an explorer were hard and resistant to solvent dissolution. The bottom surfaces that were 5 mm from the top surface and directly under the tip of the LCU were rounded 'bullet' shaped and resistant to solvent attack. The laser diode curing light used for 1 and 3 s produced the lowest scores for all 4 RBCs used in this study *(Table 5)*.

The one-way ANOVA comparing the LED and the laser curing LCUs using the nine different settings reported in Table 2 was highly significant (p-value <0.0001). Figure 8 reports the overall box plots showing the minimum, first quartile, mean, third quartile, and maximum values. The SmartLite Pro and the Valo X, both used for 2 x 10 s and the Valo X used for 2 Xtra power exposures, produced the overall best results, and the Monet used for 1 s or for 3 s produced the worst result.

DISCUSSION

The results of this study are clinically relevant for the clinician who is curing extensive restorations intraorally and wishes to use a shorter exposure time. This double-blind study was not designed to measure the hardness or degree of conversion of the RBCs. Instead, it was intended to provide the reader with visual images that showed what was cured and resistant to solvent removal, as well as what was uncured RBC. The white

Table 4. Ten highest-ranked combinations of LCUs and RBCs (descending order).

Sample #	LCU	Mode	RBC	Mean Score
38	SmartLite Pro	2x10 (standard power)	Omnichroma	4.65
140A	Valo X	2x10 (standard power)	Omnichroma	4.65
76	Valo X	2x10 (standard power)	Omnichroma	4.35
102B	SmartLite Pro	2x10 (standard power)	Omnichroma	4.35
102A	SmartLite Pro	2x10 (standard power)	Omnichroma	4.3
140B	Valo X	2x10 (standard power)	Omnichroma	4.15
37	SmartLite Pro	2x10 (standard power)	Filtek Universal	3.9
75	Valo X	2x10 (standard power)	Filtek Universal	3.8
137A	Valo X	2x10 (standard power)	Filtek Universal	3.8
80	Valo X	2x5 (Xtra power)	Omnichroma	3.65

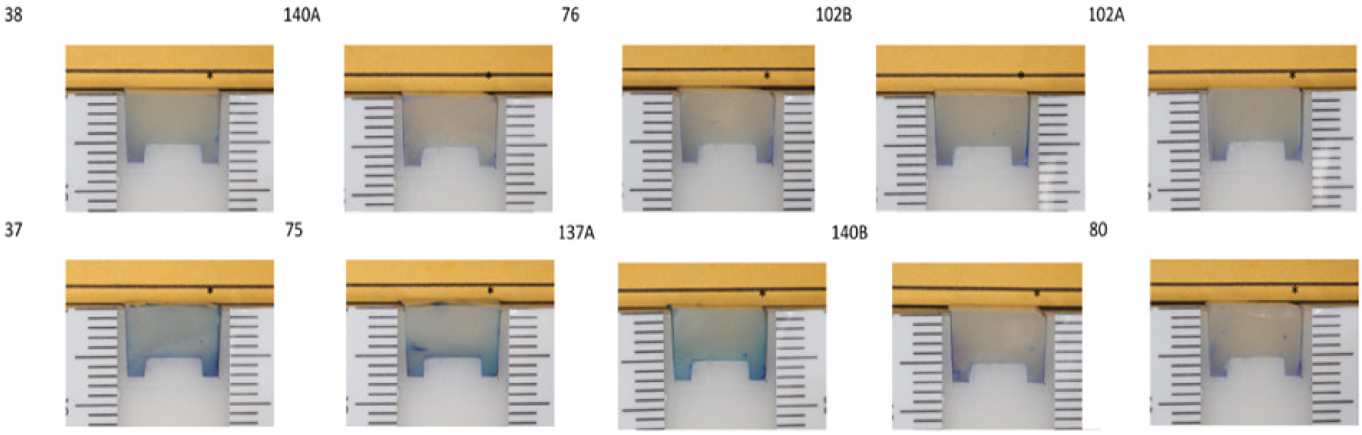

Figure 6: The ten highest-ranked samples of RBC are in descending order of best to worst (see Table 4 for the sample key).

Table 5. Ten lowest-ranked combinations of LCUs and RBCs.

Sample #	LCU	Mode	RBC	Mean Score
82	Monet	1x1	Omnichroma	1
83	Monet	1x1	SimpliShade	1
157A	Monet	1x1	Omnichroma	1
157B	Monet	1x1	Omnichroma	1
160A	Monet	1x1	Transcend	1
160B	Monet	1x1	Transcend	1
163A	Monet	1x1	Filtek Universal	1
163B	Monet	1x1	Filtek Universal	1
168A	Monet	1x1	SimpliShade	1
168B	Monet	1x1	SimpliShade	1

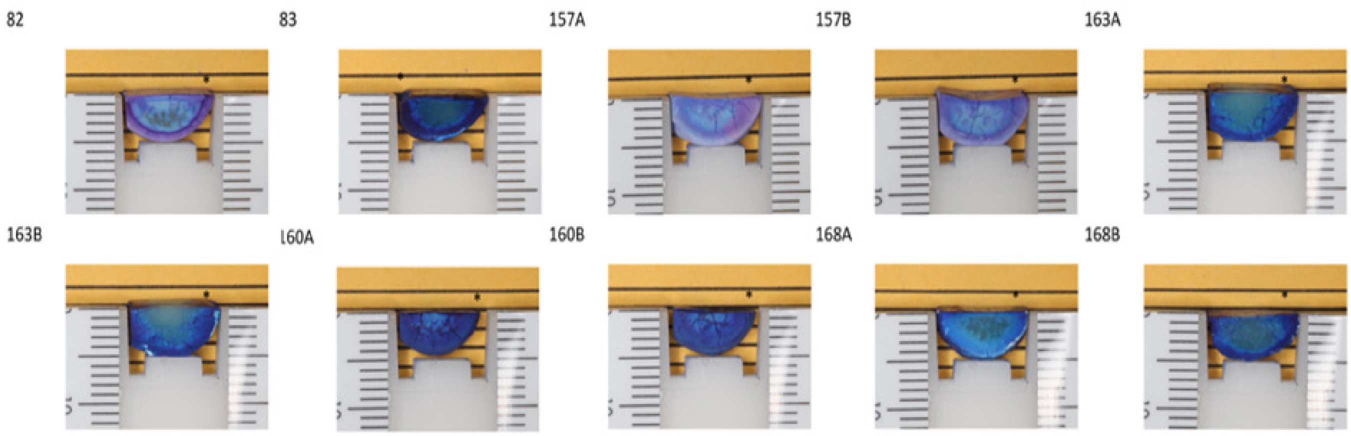

Figure 7: The ten lowest-ranked samples were light-cured with the Monet for 1 s and received a rank of 1 (see Table 5 for the sample key).

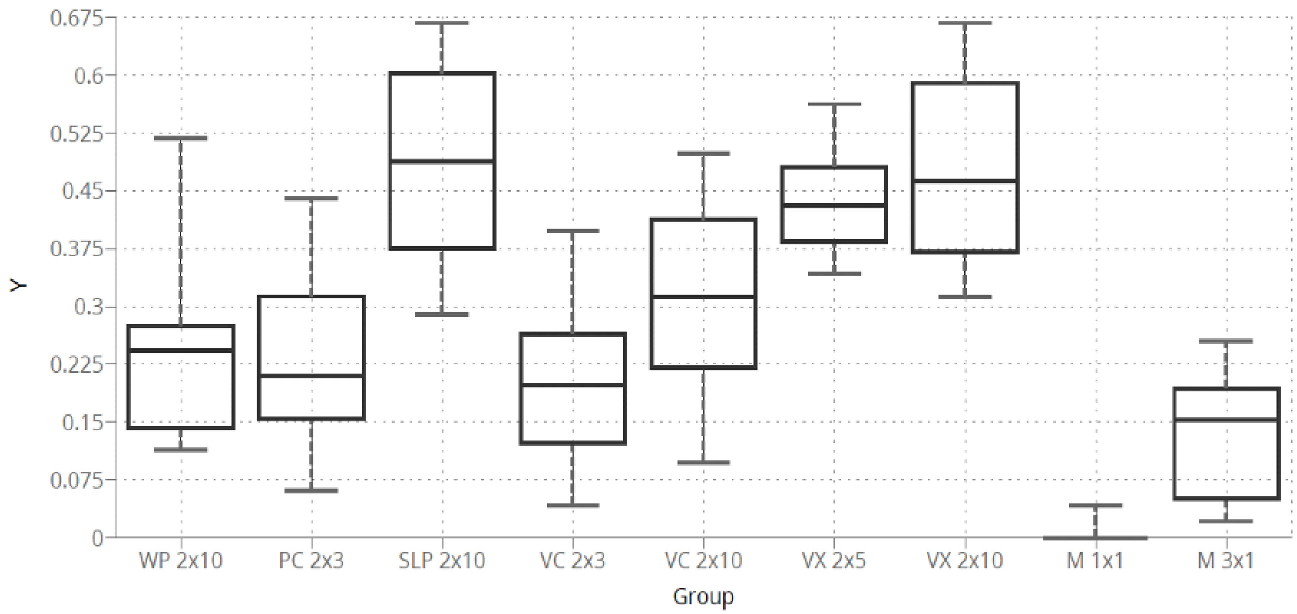

Figure 8: Box plot illustrating the overall results from all the LCUs. The data depicts the nine-number summary as the minimum, first quartile, mean, third quartile and maximum values.

Delrin MOD mold used in this study was 5 mm wide, 5 mm deep in the center, the proximal boxes were 7 mm deep, and the mesial-distal length was 12 mm. These dimensions were approximately as wide and deep as a clinical MOD restoration in a mandibular first molar.[34,83,84] Instead of using bulk-fill RBCs that should be hard and solvent-resistant to the bottom of a 7 mm deep cavity, conventional RBCs were chosen to demonstrate if and where there were differences between the LCUs. The samples were made in the same mold and in a random sequence; the uncured RBC was removed using a non-touch method and then coded and photographed. The observation that even the bottoms that were 5 mm from the top surface of the 10 specimens that were ranked to be the worst were resistant to solvent attack at 5 mm supports the choice of a 5 mm deep occlusal section in the MOD mold. The fact that the specimens were 'bullet' shaped and were only solvent resistant at the center directly underneath the tip of the LCU supports the need to use a wider mould than is currently used in the ISO 4049 standard that only measures the maximum length.

Removing the uncured dental resin using a solvent is advantageous, and several different solvents and immersion times have been used.[30,39,76-79] In this study, the RBCs were immersed in butanone, also known as methyl ethyl ketone (MEK), for one hour because butanone is an effective and common solvent that has similar properties to acetone that others have used,[76-79] but has a significantly slower evaporation rate. The digital images were analyzed at a different university by evaluators who did not know what RBCs or LCUs were being viewed. This removed all bias from the study. The result was a highly visual, apples-to-apples visual comparison that shows the reader differences between the tested LCUs in a simulated molar-sized MOD restoration.

All three hypotheses were rejected. The emission spectra, power, irradiance values, radiant exposures, and beam profiles from these 6 LCUs were not the same and two (Woodpecker B and Monet) displayed markedly non-uniform beam profiles. In addition, the 6 LCUs produced RBCs that had different resistance patterns to the solvent attack. Thus, this study confirms previous publications that have reported that the LD curing light used for 1 s does not photocure resin composites as well as LED lights used for 10 seconds.[39,55,56,73] Figure 4 shows that the laser diode LCU tested on the 1-second exposure settings delivered the lowest radiant exposure *(Table 3)*, and most of the light was delivered to the center of the MOD restoration. Even when the exposure was extended to 3 seconds, Figure 8 shows that the laser diode did not effectively photocure the bottom of the four RBC materials tested. In contrast, the LED lights used for two 10-second exposures in the standard power mode delivered the highest radiant exposures and the best and most extensively cured RBCs. Figure 7 also illustrates how erroneous results and study conclusions may be produced if the RBC specimens are only evaluated at the center. The RBCs in Figure 7 appear to be cured at the center, but then take on a convex 'bullet' shape and are uncured in the proximal boxes, where the solvent had dissolved away the RBC. Of note, the RBCs at the top and center of the MOD specimens in Figure 7 resisted dissolution by the solvent. These images are entirely different from those in Figure 6 where all of the RBCs resisted solvent dissolution. The presence of a small amount of blue stain at the edges of the specimen only indicates the edges of the specimen. Further studies that measure the hardness or degree of conversion of the RBC are required to determine how well the RBCs are photo-cured in these areas where the blue stain is evident.

The box plots reported in Figure 8 illustrate that, based on the 4 RBCs tested, the SmartLite Pro and the Valo X, both used for 2 x 10 s and the Valo X used for two Xtra power exposures produced the overall best results, and the Monet used for 1 s or for 3 s produced the worst result. Three of these four RBCs were popular products, and Omnichroma® (Tokuyama Dental Corporation) is reported to be "the first universal composite to shade match any tooth color... (which is) strong, durable, and versatile... (to) streamline the restorative process". Filtek™ Universal (3M™) is reported to be "designed to make single-shade restorations easier...with just eight designer shades, and an XW shade...(to) cover all 19 Vita classical shades and bleach shades". SimpliShade™ (Kerr® Corporation) is reported to be a "Simplified™ Universal composite with Adaptive Response Technology...featuring three shades (Light, Medium and Dark) ... (to make) quick and easy to match all 16 Vita Classical shades". The fourth RBC, Transcend (Ultradent Products, Inc.), is a new universal composite, and the universal body shade used in this study is an average dentin shade that is designed to take on the shade of the surrounding tooth structure. These 4 RBCs should all produce hard, solvent-resistant RBCs to a depth of at least 4 mm because the ISO 4049 test determines the depth of cure by photocuring 4 mm diameter specimens in a metal mold and then dividing that number by 2.[27] Since the mold was 5 mm deep in the center, all combinations of RBCs and LCUs, including the Monet, could produce a restoration resistant to a strong organic solvent at the top and at the center at the bottom that was directly under the light tip. This observation explains why the LD light can produce acceptable results in the 4 mm diameter mold used in the ISO 4049 test. However, Figure 7 shows that as the distance from the center increased, then the effect of the LCU became evident, and the RBCs became more susceptible to solvent dissolution.

As shown in Table 1, several resin manufacturers now recommend delivering a minimum irradiance of at least 500 to 550 mW/cm^2, thus delivering a minimum of 10 to 11 J/cm^2 in 10 s. When used for 20 s, most of the LCUs delivered approximately 20 J/cm², and the Valo X delivered 21 J/cm² when used for two Xtra power exposures. This explains why Figure 8 shows that the Monet, which delivered at most 4.3 J/cm² when used for 3 s, and the Valo used for 3 s in the Xtra power mode (13.9 J/cm²) were not rated as highly as the other LCUs. The observation that all the LCUs and exposure times photocured the top of the RBC directly under the center of the light tip, but at the extremes of the restoration, the RBC specimens were not so well cured was most likely due to the size of the LCU tip, and the amount of light energy delivered to the RBCs *(Table 3 and Figure 4)*. When the radiant exposure beam profile images were superimposed over the 12-mm long MOD mold *(Figure 4)*, the images show that the center of this mold received a 'hot spot' of energy from the Woodpecker B and the Bluephase PowerCure, whereas the sides of the mold received little direct energy from these LCUs. In contrast, the entire mold was covered by light from the Valo X and the Monet, but the energy delivered by the Monet in 1 s (1.4 J/cm²) was much less than from the Valo X in 20 s in the standard mode (20.8 J/cm²) or 10 s in the Xtra power mode (21.0 J/cm²). The PowerCure 2x3s, with its 8 mm internal diameter tip, also delivered less energy (18.2 J/cm²); hence, the Pairwise T-Test and Figure 8 showed that the RBCs made with this LCU were not as well cured as the SmartLite Pro (22.6 J/cm²) or the Valo X (21 J/cm²) that delivered more energy and covered more of the RBC with direct light *(Figure 4)*.

Figure 2 shows that there was a wide range in the spectral emission from these 6 LCUs, and Table 3 shows that the irradiance values from the LCUs ranged from 905 to 3035 mW/cm², and the power values ranged from 348 to 2575 mW. Table 3 and Figures 3 and 4 illustrate that even though the LCU may deliver a high irradiance, the radiant exposure may be low because the radiant exposure received by the RBC depends on the exposure time, and the irradiance depends on the tip diameter. This is why the Woodpecker B, with a tip area of 38.5 mm², delivers an irradiance of 905 mW/cm² that is similar to the Valo, which delivers 998 mW/cm² but has a tip area of 70.9 mm², yet the Woodpecker B only delivers 51% of the power and thus energy (Joules) from the Valo (348 vs. 707 mW respectively).

Also, as illustrated in Figure 3, even though the laser LCU (Monet) has a 12.5 mm internal light tip diameter, the tip beam profile is smaller than the other LCUs. This is because it is a laser, and it is technically rather challenging to make a 10+ mm diameter laser. When the images of the MOD mold are combined with the beam profiles, it appears that the curing area in this beam profile is less than half the diameter of its light tip. Figure 3 shows that these outer regions received a lower irradiance (indicated by more blue and purple colours) from the LCU, and the low radiant exposure *(Table 3 and Figure 4)* from this LCU very likely contributed to the poor results achieved by the Monet. Thus, it was not surprising that the laser LCU only cured the RBCs directly under the center of the light tip, and it failed to cure the RBCs in the proximal boxes. Also, note that the irradiance scale had to be adjusted to 12,000 mW/cm², and the 'hot spots' of high irradiance from the center of this light tip could potentially create an overheating of the RBC.

Dental students are taught how to use the LCU in dental school, but they quickly forget.[10,61-65] Although, dentists know that they need a good curing light, it has been well reported that clinicians have a poor understanding about their LCU and about light curing RBCs in the mouth.[10,21,61-64,82] Some clinicians follow the information provided by the manufacturers and only deliver one exposure to their posterior restorations.[82] In addition, it has been reported that in a study of 353 clinicians, 21% used the same light curing technique for all thicknesses of RBC, and 41% used the same technique for all types of restoration or material used.[21] This may be because translating abstract hardness and degree of conversion values from research studies into clinical performance for the practising dentist is not easy. While a 1 s light exposure will produce a hard top surface and may appear to be advantageous for the clinician, the potential unintended consequences could be dire,[18,54,57-60] and the results illustrated in Figures 6-8 should help dentists see where there were differences in how well these 6 LCUs photocured these 4 RBCs. Clinicians should now recognize that to deliver the same radiant exposure in 1 s compared to the radiant exposure delivered by the LCUs when used for 20 s, the 1 s LCU would need to deliver 20,000 mW/cm^2 across all of the light tip, not just at the center. The study also shows that multiple light exposures may be required to fully cover the RBC with light from some LCUs. Future studies should investigate the benefit of delivering additional exposures over each proximal box and the center (3+ exposures per MOD restoration) and from the side, but how this information can be translated into clinical instructions is unclear because every tooth will have different mesial-distal dimensions, thickness of remaining enamel and dentin, and different thicknesses of RBC. Since no LCU delivers 20,000 mW/cm^2 across all of the light tip, if the clinician wishes to reduce the time spent restoring a tooth, then this study suggests that it may be better if they used a bulk-fill RBC that can take half the amount of time required to restore a tooth and still produce clinical, not just laboratory, results that are equivalent to incremental filling.[68-71,85] Finally, clinicians must understand that although they currently rank irradiance as an important factor when choosing which LCU to purchase,[21] they cannot judge the performance of the LCU based on the irradiance value measured at a distance of 0 mm alone. The top surface of the RBC will always be hard even when a low radiant exposure is delivered.

CONCLUSIONS

The ability of six curing lights to photocure four resin-based composites (RBCs) in a mold that simulated a cavity was evaluated visually. The images show that photocuring RBCs using high irradiance lights for 1 to 3 s can have a detrimental effect on the outcomes of the restorative process. Within the limitations of this *in vitro* study that relied upon the susceptibility of the RBC to be dissolved by a solvent, it was concluded that:

1. There was a wide range in the emission spectra, power, tip area, and irradiance values from the six curing lights evaluated.
2. Using a curing light that delivers an adequate amount of energy over the entire RBC is critical to creating resin-based composite restorations that are resistant to solvent dissolution.
3. The Monet laser diode curing light had an irradiance 'hot spot' at the center of ~ 12,000 mW/cm² and delivered the lowest radiant exposures for both the single 1-second and the 1-x3-second exposure times.
4. The SmartLite Pro and Valo X, used for two ten-second exposures, produced restorations that were rated to be the best cured, and the Monet laser diode curing light, used for a single one-second exposure, produced restorations rated to be the least well cured.

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