



Temperature changes and hardness of resin-based composites light-cured with laser diode or light-emitting diode curing lights

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Abstract

The temperature and Vickers Hardness (VH) at the top and bottom surfaces of three resin-based composites (RBCs) were measured when light-cured using five light-curing units (LCUs). The spectrum, power, and energy delivered to the top of the RBCs and transmitted through the RBCs were measured. Starting at 32°C, the temperature rise produced by the Monet Laser (ML—1 s and 3 s), Valo Grand (VG—3 s and 10 s), DeepCure (DC—10 s), PowerCure, (PC—3 s and 10 s) and PinkWave (PW—10 s) were measured at the bottom of specimens 2 mm deep × 6 mm wide made of Filtek Universal A2, Tetric Evoceram A2 and an experimental RBC codenamed Transcend UB. The VH values measured at the top and bottom of these RBCs were analyzed using ANOVA and Scheffe's post hoc test ($p < 0.05$) to determine the effects of the LCUs on the RBCs. The transmitted power from the ML was reduced by 77.4% through 2 mm of Filtek Universal, whereas light from PW decreased by only 36.8% through Transcend. The highest temperature increases from the LCU combined with the exothermic reaction occurred for Transcend, and overall, no significant differences were detected between Filtek Universal and Tetric Evoceram ($p = 0.9756$). Transcend achieved the highest VH values at the top and bottom surfaces. The PinkWave used for 10 s produced the largest temperature increase (20.2°C) in Transcend. The Monet used for 1 s produced the smallest increase (7.8°C) and the lowest bottom:top VH ratios.

Keywords Dental curing lights · Light-emitting diode · Laser · Temperature · Vickers hardness · Hardness ratio

Introduction

The resin used in light-activated resin-based composite restorations (RBCs) must be adequately photo-cured for the restoration to be clinically successful; otherwise, the RBC remains a liquid or soft paste. Therefore, good light-curing units (LCUs) have become indispensable in the dental office. Light-emitting diode (LED) LCUs are now the most popular [1, 2]. They deliver a narrow emission range of wavelengths, they do not require any filters, they are energy efficient, and they can be battery operated [1]. Clinicians may choose to use single-peak LED LCUs that deliver only a narrow band of wavelengths, or they may use multi-peak LED LCUs,

also called polywave, that use several LEDs to emit multiple emission peaks that cover a broader range of wavelengths. Consequently, compared to single-peak LCUs, these multi-peak LED LCUs can activate a wider range of photoinitiators, as well as the commonly used camphorquinone initiator [3].

To achieve improved mechanical properties and reduce chair time, manufacturers make and promote LCUs that deliver irradiances greater than 2,000 mW/cm² and offer short exposure times, some as short as 1 s [4, 5]. However, when using LCUs that deliver a high irradiance, there is a potential risk for heat-induced pulpal injury as the RBC polymerizes [6] because the LCU can deliver a considerable amount of energy [7] to the gingivae [8, 9] and the pulpal tissues [10–16]. In addition, the exothermic polymerization reaction produces additional heat that increases the magnitude of the temperature rise. Thus, the temperature rise in the tooth depends on the RBC, power (Watts), irradiance (mW/cm²), exposure time, amount of energy delivered (Joules), the rate at which the RBC polymerizes, and the wavelengths of light delivered from the LCU [3,

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17–22]. It has been suggested that temperature increases greater than 5.5 °C inside the pulp chamber might be dangerous to the pulp [10]. For this reason, the heat generated when using LCUs that deliver an irradiance greater than 1,200 mW/cm² has become a concern [22].

A new approach to the photo-activation of composites uses a fast, 1–3-s light exposure at a high irradiance [23–25]. A recent development uses a laser diode LCU to deliver such a high irradiance at 450 nm in a 1-s exposure (Monet, AMD). The manufacturer claims that this laser diode LCU has a collimated beam that allows the light to penetrate deeply into the RBC and photo-cure the RBC to a depth of 2 mm in only 1 s. Some blue diode lasers using 445 nm have already been tested as an alternative light source to photo-cure dental RBCs [26, 27]. Since they are a laser, they deliver a high photon density and a high irradiance even as the distance from the light tip increases, but their output is over a very narrow range of wavelengths [26]. A previous study reported that using one laser diode LCU for 1 s produced the shallowest depth of cure in all ten RBCs tested. This was attributed to the low radiant exposure delivered by this LCU in 1 s. [28]. Another new LCU is the PinkWave. This LCU has what the manufacturer describes as Quadwave technology to deliver four distinct bands of wavelengths over a wider range of wavelengths than conventional LCUs. In addition to blue and violet light, the PinkWave delivers near-infrared (NIR) and red light. However, there is currently no information regarding the temperature rise that occurs when using the Monet or the PinkWave LCUs.

Some previous laboratory studies have evaluated the heat generated on cylindrical RBC specimens made in Teflon molds at room temperature using both K- and T-type thermocouples [18, 19, 27, 29]. Alternatively, high-definition digital infrared imagery has been used to monitor the temperature [22, 30]. However, in these studies, the volume of RBCs used was often not well defined, the energy or the wavelengths delivered by the LCU were not reported, nor was a baseline temperature used that was similar to the intra-oral temperature found in a tooth [15, 30]. Therefore, this study recorded the real-time temperature rise produced at the bottom of standardized volumes of three RBCs using a fast response T-type thermocouple starting at a simulated intra-oral temperature of 32°C [15] when light-cured using five different LCUs. In addition, the light transmission through the RBCs and the Vickers micro-hardness (VH) at the top and bottom surfaces were measured.

The null research hypotheses are that:

- (1) The five LCUs would not deliver the same amount of energy (Joules);
- (2) The combined effect of the light from the LCUs and the exothermic reaction would not produce the same temperature increase at the bottom of the three RBCs;

- (3) There would be no differences in the exothermic temperature rise produced by different RBCs;

- (4) The exothermic heat contribution to the temperature increase would not be greater than 5.5°C [10]; and.

- (5) There would be no differences in hardness values at the top and bottom of the RBCs when the different LCUs were used.

Materials and methods

Resin-based composites (RBCs) and light-curing units (LCUs)

Three conventional paste consistency RBCs whose manufacturers recommend a 2 mm maximum increment thickness were used in the study: Tetric Evoceram A2 (Ivoclar Vivadent, Schaan, Liechtenstein); Filtek Universal A2 (3 M Oral Care, St. Paul, MN, USA) and one experimental RBC codenamed Transcend UB (Ultradent, South Jordan, Utah, USA). The lot numbers and manufacturers are reported in Table 1.

Five contemporary high-output LCUs were used: Deep-Cure (DC, 3M Oral Care, St. Paul, MN, USA), PinkWave (PW, Vista Dental Products, Racine, WI, USA), Power-Cure (PC, Ivoclar Vivadent, Schaan, Liechtenstein), Valo Grand (VG, Ultradent Products Inc., South Jordan, UT, USA), and Monet Laser (ML, AMD Lasers, West Jordan, UT, USA). The brand, serial number, manufacturer, type, emission spectrum (nm), the exposure modes recommended by the manufacturer to light cure 2 mm of RBC [4, 31–34] and their claimed irradiance outputs are reported in Supplemental Table 1.

Analysis of the light emitted by the LCUs and transmitted through the RBCs

A 2 mm thick semi-transparent Delrin (polyoxymethylene homopolymer) mold with a 6 mm diameter hole was used in the study to measure the temperature changes, the light received by the specimens from the LCU, and the amount of light transmitted through the RBCs. First, the irradiance was measured through the unfilled Delrin mold placed between the LCU tip and the entrance into a 6" integrating sphere (Labsphere, North Sutton, NH, USA). This sphere was attached to a fiber-optic Flame spectrometer (Ocean Insight, Logan, FL, USA). This entire measurement system had been previously calibrated using an internal calibration lamp SCL-600 (Labsphere). Next, the tip of each LCU was centrally positioned at the entrance to the 6 mm diameter hole, and the light output from each LCU through the hole in the mold and into the sphere was measured. Of note, this was not the irradiance emitted at the tip of the LCU; instead,

Table 1 Manufacturer's information about the RBCs

Composite	Lot number	Manufacturer	Shade	Matrix resin composition	Inorganic filler composition	Inorganic filler content (%)
Filtek Universal	NE15442	3M Oral Care, St Paul, MN, USA	A2	AUDMA, AFM, diurethane-DMA, and 1,12-dodecane-DMA	Non-agglomerated/non-aggregated 20 nm silica filler, a non-agglomerated/non-aggregated 4–11 nm zirconia filler, an aggregated zirconia/silica cluster filler (comprised of 20 nm silica and 4–11 nm zirconia particles), and a ytterbium trifluoride filler consisting of agglomerated 100 nm particles	76.5% by weight (58.4% by volume)
Tetric Evoceram	X22319	Ivoclar Vivadent, Schaan, Liechtenstein	A2	Dimethacrylates (17–18% weight)	Barium glass, ytterbium trifluoride, mixed oxide and prepolymer. Particle size between 40 nm and 3,000 nm with a mean particle size of 550 nm	75–76% by weight (53–55% by volume)
Transcend	RN776	Ultradent Products Inc., South Jordan, UT, USA	UB	Five different resin monomers described as functional methacrylates	Five different types of silicate fillers ranging in size from 5 nm to 3µm	77.5% by weight

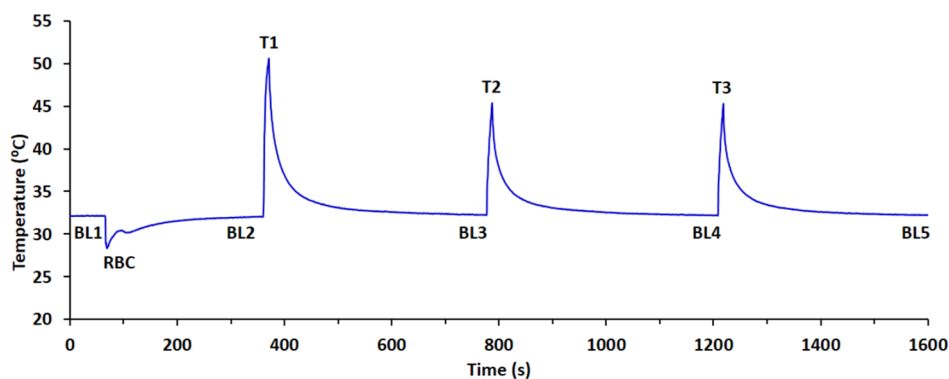
it was the same irradiance received by the 6 mm diameter specimens. Then, additional Delrin molds were filled with the RBCs used in the study and photo-activated with the PowerCure for 20 s. These molds were then placed at the entrance of the integrating sphere, and the light that passed through the cured RBC and into the sphere was measured for each LCU condition (Supplemental Table 1). Three measurements were made for each group to obtain the mean powers (mW), radiant exposures (J/cm^2), and the attenuated powers of the light that reached the bottom of each RBC.

Temperature analysis

The same 2 mm thick semi-transparent Delrin mold with a 6 mm diameter hole (volume of 56.5 mm^3 ($V = \pi r^2 h$) for each specimen) was placed on a block of cured Filtek Supreme Ultra Shade A2 RBC (3 M Oral Care, St. Paul, USA) that was 31 mm wide by 57 mm long. A fast response thermocouple T-type (Physitemp Instruments, Clifton, USA) was placed on the block, centrally at the bottom of the specimen, and the temperature was recorded in real-time (every 0.5 s) with the T-type thermocouple connected to a temperature acquisition software (T.C. Chart 1.03, Nomadics Inc., USA). The block was placed on top of a warming plate (Cimarec, Thermo Fisher Scientific, Waltham, USA) set at 32°C and the temperature was

monitored in real-time until it stabilized. A thin layer of zinc oxide thermal paste (Corsair Memory, Almere, Netherlands) was placed over the thermocouple to improve the temperature transfer from the RBC to the thermocouple. Once the baseline temperature had reached 32°C [15], the 6 mm diameter hole in the Delrin ring was filled with RBC. This caused the temperature to fall, but once the baseline temperature had returned to 32°C , the RBCs in each group were exposed to light with the tip of the LCU positioned 0 mm from the surface of the RBC. An example of how the three temperature measurements were made is shown in Fig. 1. After the RBC specimens had been exposed to light, the LCU was taken out of contact with the surface of the RBC so that the light tip did not act as a thermal heat sink. The temperature was monitored in real-time until it returned to 32°C , at which time an additional light exposure was performed. The samples received this second light exposure to hopefully fully photo-polymerize the RBC. This was then followed by a third exposure. The resulting temperature rise was used to calculate the exothermic heat contribution from the RBCs by subtracting this temperature rise (ΔT_3) from the first (ΔT_1) temperature rise. The time to reach the maximum temperature (T_1 peak) and then return to 32°C was approximately 6 min. A total of five temperature measurements ($n = 5$) were made for each group.

Fig. 1 Example of one of the temperature measurements (Tetric Evoceram + PW 10 s). BL: Baseline; RBC: Insertion of the composite into the mold; and T: temperature rise for each LCU exposure. Note that the BL values returned to 32°C after every exposure



Vickers micro-hardness (VH)

After temperature measurements had been made, the specimens ($n=5$) were removed from the Delrin mold and stored in dry and dark conditions for 24 h. The RBCs were weighed using a Mettler AE 160 digital scale (Mettler Toledo Instruments, Ontario, Canada) to confirm that the specimens were similar. The Vickers hardness (VH) was then measured using a micro-hardness testing machine (HM 123, Mitutoyo, Kawasaki, Kanagawa, Japan) that applied a 300 g load for 8 s [35]. Three equidistant indentations were made close to the center of the unpolished top and bottom surfaces.

Statistical analysis

The present study consisted of 2 independent variables (“RBC” and “LCU”), with the factor “RBC” containing 3 sublevels and “LCU” with 8 sublevels. The factorial scheme resulted in 24 experimental groups, with 5 repetitions for each group ($n=5$). The ΔT values were subjected to a two-way, repeated-measures analysis of variance (ANOVA) test with “RBC” and “exposure modes” as the independent variables, followed by Scheffe’s post hoc tests. The specimen weight, time to take the maximum temperature, exothermic heat contribution and VH values among the products were compared using one-way ANOVA followed by Scheffe’s post hoc test. All statistical testing and post hoc analyses were conducted using a preset α of 0.05. Logarithmic regression analyses were performed (Excel, Microsoft, Redmond, WA, USA) for each RBC temperature rise at the different exposure modes using either the Power (Watts) or the Energy (Joules) delivered from the LCUs to the RBCs.

Results

Weight

Overall, the specimens made using Tetric Evoceram had the highest mean \pm standard deviation weight value of 0.120 ± 0.005 g, followed by Transcend UB at 0.117 ± 0.005 g and Filtek Universal A2 at 0.115 ± 0.004 g.

These differences of ± 0.005 g represented, at most, a 4% difference in the weight of the RBCs in each group. No significant differences were found between the Filtek Universal A2 and Transcend UB groups of RBC ($p=0.2658$), but Scheffe’s post hoc test detected a significant difference for the specimens of Tetric Evoceram ($p < 0.05$).

Analysis of the light emitted by the LCUs and transmitted through the RBCs

Figure 2 shows the total power (mW) and emission spectra from the LCUs. The Valo Grand, PowerCure and PinkWave were multi-peak broadband LED lights. The PowerCure delivered two wavelength peaks, and the Valo Grand had three peaks. One peak was in the violet range (Valo Grand = 393 nm and PowerCure = 408 nm), and the others were in the blue wavelength region (Valo Grand at 448 and 461 nm and PowerCure = 451 nm). The PinkWave LCU emitted four distinct bands of wavelengths, three were in the range of visible light ($\lambda_1=410$ nm; $\lambda_2=471$ nm, $\lambda_3=631$ nm), and one was in the near-infrared spectral range (thermal radiation) with an emission peak (λ_4) at 860 nm. The Monet and DeepCure LCUs delivered only a single emission peak (Fig. 2). The DeepCure emitted a broader range of wavelengths with a peak emission at 448 nm. Since the Monet is a laser, it emitted a very narrow band of wavelengths with an emission peak at 451 nm.

The power (mW) transmitted through the empty mold and through the molds filled with RBC are reported in Table 2. The transmitted power from the ML was reduced by 77.4% when passing through 2 mm of Filtek Universal A2, whereas the power of the light from the PW decreased by only 36.8% after passing through 2 mm of Transcend UB. Figure 3 shows the emission spectra from PinkWave and Valo Grand through the empty ring and the ring filled with the RBCs. Note the greater reduction of the lower wavelengths of violet light. Table 3 reports the irradiance and radiant exposure received by the RBCs in the 6 mm diameter mold. Note that the radiant exposure delivered in every single exposure ranged from a little as 5.4 J/cm² to a high of 31.0 J/cm², depending on the LCU and exposure time. This value must

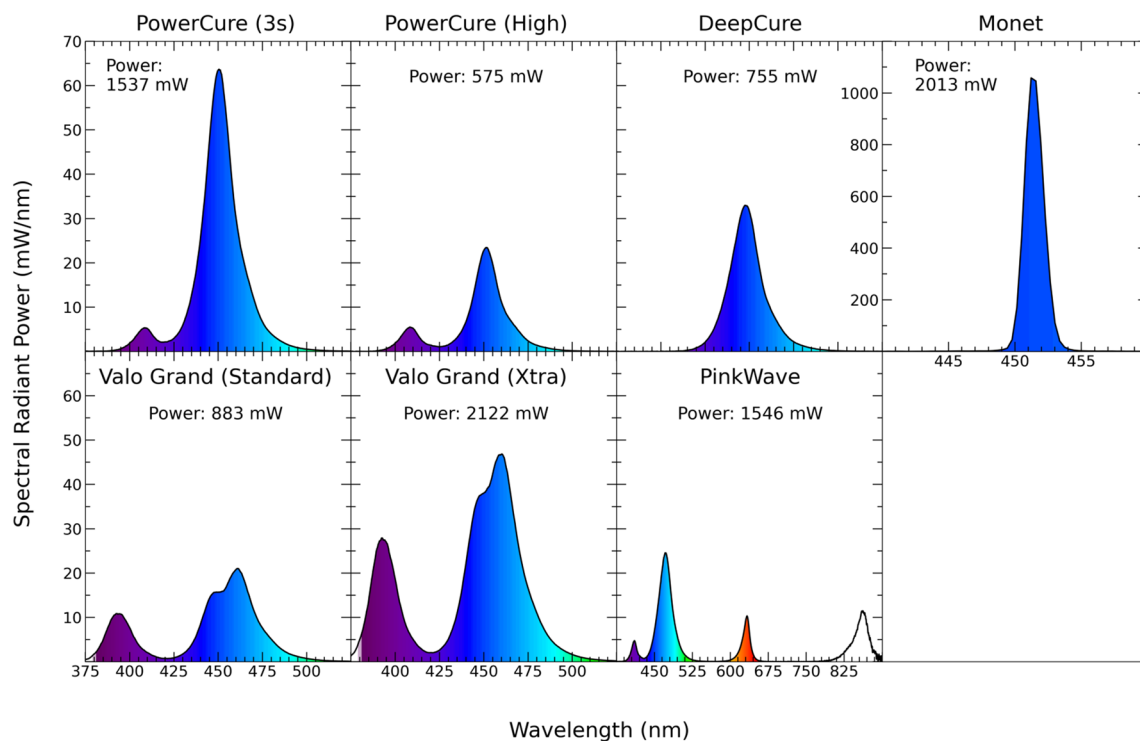


Fig. 2 Total Power (mW) and Emission Spectra from the LED LCUs and from Monet Laser LCU. Note this was not the power received by the 6 mm specimens, and the different power and wavelength scales for Monet Laser

be multiplied by 3 to give the total radiant exposure delivered to the RBCs after they had received 3 light exposures.

Temperature analysis

The greatest mean temperature (\pm Standard Deviation) increases during the first light exposure of the RBCs, regardless of the exposure mode, occurred at the bottom of Transcend UB (mean $\Delta T_1 = 17.2^\circ\text{C}$, $SD = 4.4$), followed by Tetric Evoceram A2 (mean $\Delta T_1 = 13.1^\circ\text{C}$, $SD = 3.1$) and Filtek Universal A2 (mean $\Delta T_1 = 13.0^\circ\text{C}$, $SD = 3.1$). Scheffe's test detected a significant difference for Transcend ($p < 0.0001$), but there was no significant difference between the temperature increase for Filtek Universal and Tetric Evoceram ($p = 0.9756$).

The greatest temperature increase was found when the PinkWave was used for 10 s (mean $\Delta T_1 = 20.2^\circ\text{C}$, $SD = 2.2$), regardless of the RBC used. The smallest temperature increase was from the Monet when used for 1 s (mean $\Delta T_1 = 7.8^\circ\text{C}$, $SD = 0.6$). No significant differences were found between PowerCure used for 10 or 3 s, Valo Grand used for 10 or 3 s, DeepCure used for 10 s, and the Monet used for 3 s (Fig. 4). Except for Monet used for 1 s, the temperature rises on the two subsequent exposures of the now cured RBC were significantly lower, but again the

PinkWave used for 10 s produced the greatest overall temperature increase (Table 4 and Fig. 4).

Logarithmic regression analyses examined the relationship between the combined exothermic and LCU temperature rises and either the Power (Watts) or the Energy (Joules) delivered by the LCUs to the RBCs. For all the RBCs, Fig. 5 shows no correlation between the power output from the LCUs and the temperature rise ($R^2 = 0.0067$ for Filtek Universal, $R^2 = 0.0177$ for Tetric Evoceram and $R^2 = 0.0027$ for Transcend). However, there was an excellent positive correlation between the energy delivered from the LCU and the temperature rise at the bottom of the RBC ($R^2 = 0.827$ for Filtek Universal, $R^2 = 0.763$ for Tetric Evoceram and $R^2 = 0.721$ for Transcend).

Table 5 reports the mean and standard deviation time (s) the RBCs took to reach their respective maximum temperatures and then return to 37°C . After the initial first exposure, Filtek Universal exposed to the Deep Cure for 10 s ($11.8 \text{ s} \pm 1.6$) and Transcend exposed to the PinkWave for 10 s ($11.0 \text{ s} \pm 0.5$) took the longest to reach their maximum temperature. The RBCs exposed to the PinkWave used for 10 s took the longest time to return to 37°C ($32.4 \text{ s} \pm 3.5$ for Transcend, $29.6 \text{ s} \pm 3.5$ for Filtek and $29.0 \text{ s} \pm 3.0$ for Tetric Evoceram).

The exothermic heat contribution from each RBC was calculated by subtracting the third temperature rise (ΔT_3)

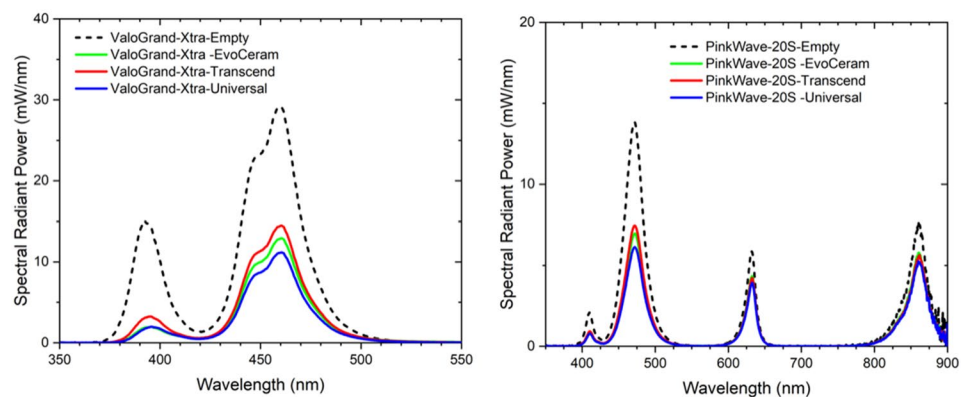
Table 2 Transmitted power (mW) means and standard deviations (SD) through the empty mold and through the mold filled with cured RBC, difference (mW), and percentage reduction (%)

RBC and LCU	Power through empty mold (mW)		Power through mold filled with RBC (mW)		Difference (mW)	Percentage reduction (%)
	Mean	SD	Mean	SD		
Filtek Universal + ML	1538	45.1	347	2.4	1191 ^A	77 ^A
Tetric Evoceram + ML	1538	45.1	401	3.7	1136 ^B	74 ^{BC}
Transcend + ML	1538	45.1	542	0.6	995 ^C	65 ^H
Filtek Universal + VG xtra	1268	5.9	418	1.9	850 ^D	67 ^F
Filtek Universal + PC 3 s cure	1108	15.0	280	5.4	828 ^E	75 ^B
Tetric Evoceram + PC 3 s cure	1108	15.0	315	0.7	793 ^F	72 ^D
Tetric Evoceram + VG xtra	1268	5.9	484	3.1	784 ^F	62 ^J
Transcend + PC 3 s cure	1108	15.0	393	1.6	715 ^G	65 ^H
Transcend + VG xtra	1268	5.9	555	2.8	713 ^G	56 ^K
Filtek Universal + DC	535	4.3	143	0.9	392 ^H	73 ^C
Filtek Universal + PW	875	7.8	489	0.8	386 ^H	44 ^L
Tetric Evoceram + DC	535	4.3	160	0.3	375 ^I	70 ^E
Filtek Universal + VG standard	529	2.6	180	0.6	349 ^J	66 ^G
Transcend + DC	535	4.3	198	0.9	337 ^K	63 ^I
Tetric Evoceram + PW	875	7.8	541	0.7	334 ^K	38 ^M
Tetric Evoceram + VG standard	529	2.6	206	1.2	323 ^L	61 ^J
Transcend + PW	875	7.8	553	0.9	322 ^L	37 ^N
Filtek Universal + PC high	408	4.5	103	1.1	305 ^M	75 ^B
Transcend + VG standard	529	2.6	235	0.6	294 ^N	56 ^K
Tetric Evoceram + PC high	408	4.5	115	0.7	293 ^N	72 ^D
Transcend + PC high	408	4.5	144	0.5	264 ^O	65 ^H

Note the low percentage reduction (%) for PinkWave

Means followed by similar uppercase superscript letters (within the column) are not significantly different (Scheffe's post hoc test, $p \geq 0.05$)

Fig. 3 Emission Spectra (mW/nm) from PinkWave and Valo Grand through the empty molds and through the molds filled with RBC. Note that the x axis for the Pinkwave is on a different \geq scale



from the first temperature rise (ΔT_1). Figure 6 shows the exothermic heat contribution for each group. Except for Monet used for 1 s ($1.4^\circ\text{C} \pm 0.3$), the highest exothermic heat contributions from the RBC were found at the bottom of Transcend (temperatures ranging between $8.2^\circ\text{C} \pm 0.7$ and $11.2^\circ\text{C} \pm 1.0$).

Overall, when comparing the RBCs, irrespective of which LCU was used, Transcend produced the greatest ($p < 0.05$) exothermic temperature rise ($8.1^\circ\text{C} \pm 2.8$). However, Scheffe's post hoc test found no significant difference ($p = 0.4935$) between the overall exothermic temperature

Table 3 Exposure time (s), mean power (mW) values and standard deviation (SD), irradiance (mW/cm²), and radiant exposure (J/cm²) delivered to the RBCs in the 6 mm diameter Delrin mold

Light curing unit	Exposure time (s)	Power (mW)		Irradiance (mW/cm ²)	Radiant exposure (J/cm ²)
		Mean	SD		
Monet	1	1538	45.1	5441	5.4
PowerCure 3s Mode	3	1108	15.0	3921	11.8
Valo Grand Xtra Power Mode	3	1268	5.9	4485	13.5
PowerCure High Power Mode	10	408	4.5	1445	14.5
Monet	3	1538	45.1	5441	16.3
Valo Grand Standard Mode	10	529	2.6	1873	18.7
DeepCure	10	535	4.3	1894	18.9
PinkWave	10	875	7.8	3096	31.0

Table 4 Mean and standard deviation (SD) temperature increase in the RBCs caused by the different LCUs and exposure times ranked from greatest to least temperature increase

RBC	LCU and exposure time	ΔT1		ΔT2		ΔT3				
		Mean	SD	Mean	SD	Mean	SD			
Transcend	PW 10 s	22.8	1.1	Aa	14.1	0.6	Ab	14.0	0.6	Ab
Transcend	VG 3 s	19.5	1.6	ABa	8.8	0.9	BCDEFb	8.3	0.9	BCDEFb
Transcend	ML 3 s	19.5	0.7	ABa	11.2	1.0	ABCDB	11.2	0.8	ABCDB
Tetric Evoceram	PW 10 s	19.2	1.0	ABCa	13.6	0.4	ABb	13.5	0.7	ABb
Transcend	DC 10 s	18.8	1.4	ABCDa	9.8	0.7	ABCDEb	9.8	0.7	ABCDEb
Filtek Universal	PW 10 s	18.5	0.7	ABCDEa	12.1	0.7	ABCb	12.0	0.7	ABCb
Transcend	PC 3 s	18.4	1.2	ABCDEFa	8.9	0.8	BCDEFb	8.8	0.5	BCDEFb
Transcend	VG 10 s	16.3	0.9	BCDEFGa	8.1	0.5	CDEFb	8.2	0.6	CDEFb
Tetric Evoceram	ML 3 s	15.0	1.6	BCDEFGHa	8.7	1.8	BCDEFb	8.3	1.6	BCDEFb
Filtek Universal	ML 3 s	14.7	1.4	BCDEFGHa	7.9	1.0	CDEFb	7.6	0.8	CDEFb
Transcend	PC 10 s	14.5	0.8	CDEFGHa	6.2	0.2	DEFb	6.1	0.1	DEFb
Tetric Evoceram	DC 10 s	13.9	0.9	DEFGHa	8.4	0.4	CDEFb	8.1	0.4	CDEFb
Filtek Universal	VG 3 s	13.6	0.4	DEFGHa	6.0	0.5	EFb	5.8	0.4	EFb
Tetric Evoceram	VG 3 s	13.6	0.8	EFGHa	6.4	0.4	DEFb	6.3	0.4	DEFb
Filtek Universal	DC 10 s	13.2	1.5	FGHla	7.2	0.9	CDEFb	6.8	1.1	DEFb
Filtek Universal	VG 10 s	12.7	1.1	GHIJa	6.0	0.3	EFb	6.1	0.4	DEFb
Tetric Evoceram	VG 10 s	12.4	0.3	GHIJKa	6.6	0.3	DEFb	6.6	0.3	DEFb
Filtek Universal	PC 3 s	12.2	1.2	GHIJKa	5.4	0.7	EFb	5.5	0.6	EFb
Tetric Evoceram	PC 3 s	12.1	1.3	GHIJKa	6.0	0.3	EFb	6.1	0.5	DEFb
Filtek Universal	PC 10 s	11.2	1.6	GHIJKa	5.2	0.7	EFb	5.2	0.7	EFb
Tetric Evoceram	PC 10 s	10.9	1.1	HIJKa	5.6	0.5	EFb	5.5	0.3	EFb
Tetric Evoceram	ML 1 s	8.2	0.7	IJKa	3.9	0.6	Fa	4.0	0.8	Fa
Transcend	ML 1 s	7.7	0.8	JKa	6.2	0.8	DEFa	6.3	0.9	DEFa
Filtek Universal	ML 1 s	7.5	0.2	Ka	3.8	0.2	Fa	3.9	0.4	Fa

Means followed by similar superscript letters (lowercase: within the row; uppercase: within the column) are not significantly different (Scheffe’s post hoc test, $p \geq 0.05$)

increases of Filtek Universal ($6.4^{\circ}\text{C} \pm 1.4$) and Tetric Evoceram ($5.8^{\circ}\text{C} \pm 1.0$).

Vickers micro-hardness (VH)

Table 6 reports the mean and standard deviation VH values at the top and bottom surfaces of the 2 mm thick specimens after they had received three light exposures. The bottom:top

ratio for each RBC and LCU was calculated by dividing the bottom to the top values for the same condition of RBC and LCU. In addition, the bottom:top ratio for each RBC was calculated based on the greatest mean VH value at the top achieved using any LCU for that RBC, divided by the bottom VH value. Scheffe’s post hoc test detected a significant difference between the surfaces for Filtek Universal and Tetric Evoceram ($p = 0.0015$). No difference between top and

Fig. 4 Overall mean temperature increase (ΔT) as the three uncured RBCs were exposed to the different exposure modes. The line over the columns shows where there was no significant difference between exposure modes (Scheffe's post hoc test $p \geq 0.05$). Note that the largest increase in the temperature occurred using the PinkWave for 10 s

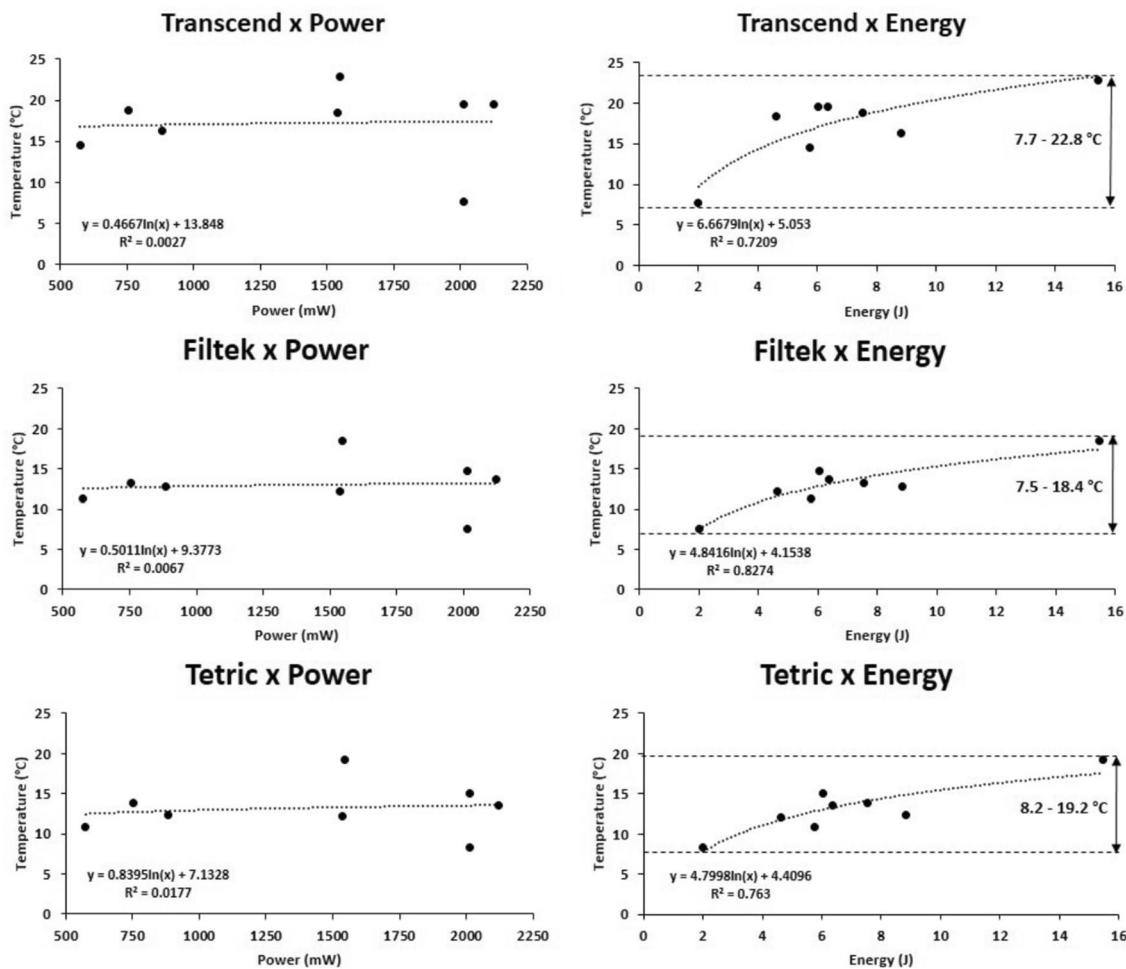
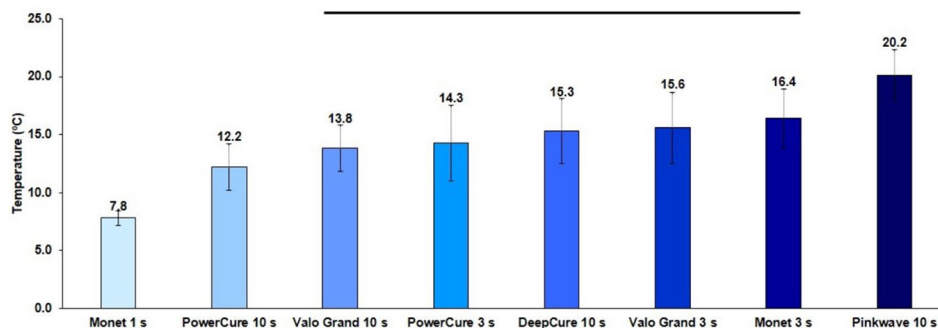


Fig. 5 Semi-logarithmic regression for Transcend, Filtek Universal and Tetric Evoceram RBCs temperature rise recordings for the different exposure modes when analyzing the different effects of the Power and Energy from the LCU

bottom was detected for Transcend ($p = 0.3594$). Although a significant difference was detected for Filtek Universal and Tetric Evoceram, the percentage differences between the top and bottom were low (Filtek Universal = 3.3% and Tetric Evoceram = 7.6%).

Figure 7 shows the mean VH values for each exposure mode used in the study, regardless of the RBC used. Overall, the Valo Grand used for 10 s produced the highest VH values, whereas the Monet, used for both 1 s and 3 s, achieved the lowest VH values. Although the specimens were harder

Table 5 Mean and Standard Deviation (SD) time (s) taken for the temperature to reach the maximum temperature (T1 peak) and then return to 37°C

RBC	LCU and exposure time	Time to reach the maximum temperature (s)			Time to return to 37°C (s)		
		Mean	SD		Mean	SD	
Filtek Universal	DC 10 s	11.8	1.6	A	19.1	3.5	BCDEF
Transcend	PW 10 s	11	0.5	A	32.4	3.5	A
Tetric Evoceram	PC 10 s	10.8	1.0	A	12.2	2.6	EF
Filtek Universal	VG 10 s	10.7	1.3	A	22.3	4.5	ABCDEF
Filtek Universal	PW 10 s	10.6	1.0	A	29.6	3.5	AB
Tetric Evoceram	PW 10 s	10.5	0.4	A	29	3.0	ABC
Tetric Evoceram	VG 10 s	10.4	1.0	A	20	3.7	BCDEF
Tetric Evoceram	DC 10 s	10.3	0.8	A	16.9	1.5	DEF
Filtek Universal	PC 10 s	10.2	0.6	A	12.7	5.0	EF
Transcend	DC 10 s	9.7	1.0	A	22.6	2.2	ABCDEF
Transcend	VG 10 s	9	1.5	A	24.6	4.3	ABCD
Transcend	PC 10 s	8.5	1.7	AB	20	3.6	BCDEF
Tetric Evoceram	ML 3 s	5.1	0.9	BC	19.9	2.0	BCDEF
Tetric Evoceram	VG 3 s	5.1	0.8	BC	22.2	1.2	ABCDE
Filtek Universal	VG 3 s	4.9	0.5	C	22	0.9	ABCDEF
Filtek Universal	PC 3 s	4.7	0.4	C	17.7	4.3	CDEF
Tetric Evoceram	PC 3 s	4.7	1.3	C	16.4	2.2	DEF
Transcend	ML 3 s	4.6	0.4	C	26.9	2.2	ABCD
Transcend	ML 1 s	4.6	0.4	C	10.3	1.5	F
Filtek Universal	ML 3 s	4.4	0.4	C	24.5	2.2	ABCD
Transcend	PC 3 s	4	0.9	C	23.5	2.3	ABCDEF
Tetric Evoceram	ML 1 s	3.6	0.4	C	9.4	2.1	F
Filtek Universal	ML 1 s	3.4	0.4	C	10.1	1.2	F
Transcend	VG 3 s	3.2	0.6	C	26	2.0	ABCD

Means followed by similar uppercase superscript letters (within the column) are not significantly different (Scheffe’s post hoc test, $p \geq 0.05$)

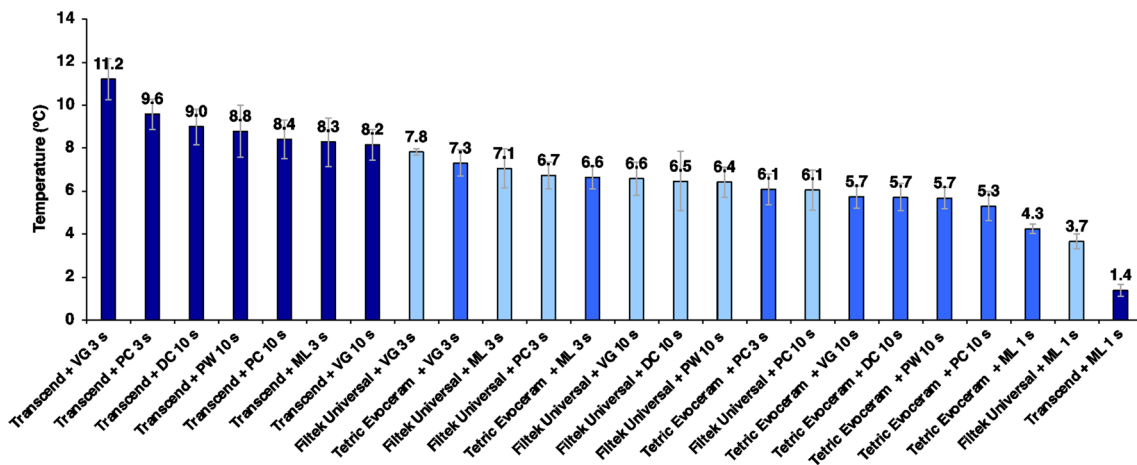


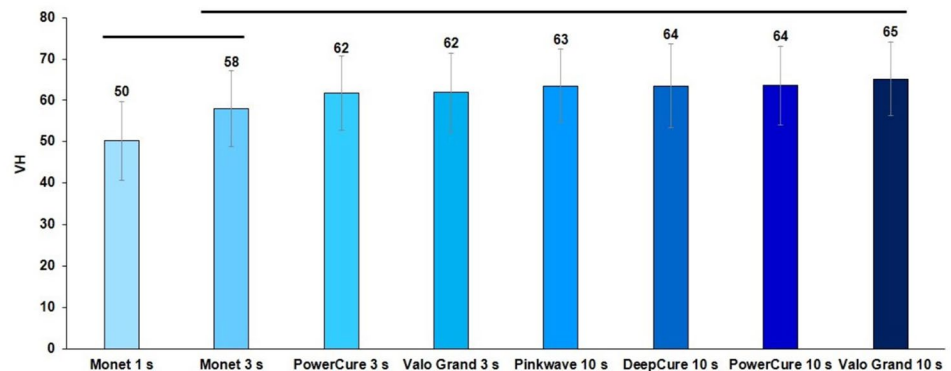
Fig. 6 Contribution of the exothermic reaction to the temperature rise (mean ± standard deviation) caused by the different LCUs and exposure times

Table 6 Mean \pm standard deviation (SD) Vickers hardness (VH) at the top and bottom surfaces of the RBCs after three repeated exposures using the different LCUs and exposure times

RBC, LCU and exposure time (s)	Top VH		Bottom VH		Top/bottom ratio for each RBC and LCU	Top/bottom ratio for each RBC based on the highest VH at the top
	Mean	SD	Mean	SD		
Transcend + VG 10 s	75.0	2.2	73.5	2.3	0.98	0.98
Transcend + DC 10 s	74.5	0.9	71.7	2.0	0.96	0.96
Transcend + PC 10 s	74.5	1.2	72.3	1.7	0.97	0.96
Transcend + PW 10 s	74.3	0.8	71.9	2.7	0.97	0.96
Transcend + VG 3 s	72.7	1.8	72.7	0.9	1.00	0.97
Transcend + PC 3 s	69.9	1.2	67.5	2.4	0.97	0.90
Filtek Universal + DC 10 s	68.9	1.6	65.4	1.5	0.95	0.95
Filtek Universal + PC 3 s	68.1	2.0	65.0	1.9	0.96	0.94
Filtek Universal + VG 10 s	68.0	1.2	66.3	2.2	0.97	0.96
Filtek Universal + PC 10 s	67.1	1.0	64.7	1.4	0.96	0.94
Filtek Universal + ML 3 s	65.7	2.1	64.4	2.1	0.98	0.93
Filtek Universal + PW 10 s	64.9	2.4	64.8	1.6	1.00	0.94
Filtek Universal + VG 3 s	63.8	3.2	60.0	1.6	0.94	0.87
Transcend + ML 3 s	63.1	3.0	63.1	2.0	1.00	0.84
Filtek Universal + ML 1 s	61.1	1.1	59.5	2.3	0.97	0.86
Tetric + VG 10 s	56.7	3.0	51.5	1.9	0.91	0.91
Tetric + PC 10 s	54.3	1.3	48.5	2.0	0.89	0.85
Tetric + VG 3 s	54.3	1.9	47.9	1.7	0.88	0.84
Tetric + PW 10 s	54.0	2.0	51.0	1.1	0.95	0.90
Transcend + ML 1 s	52.7	1.6	51.8	2.3	0.98	0.69
Tetric + PC 3 s	52.6	3.1	47.0	1.0	0.89	0.83
Tetric + DC 10 s	51.9	0.7	48.9	3.4	0.94	0.86
Tetric + ML 3 s	45.4	3.0	45.8	1.5	1.01	0.81
Tetric + ML 1 s	39.4	1.5	37.0	2.3	0.94	0.65

Top/Bottom Ratios for each RBC and LCU and the Top/Bottom Ratios for each RBC based on the highest mean VH achieved at the Top

Fig. 7 Combined mean \pm standard deviation (SD error bars) VH values for all the RBCs for each exposure mode. The lines over the columns show where there was no significant difference between the different exposure modes (Scheffe's post hoc test $p \geq 0.05$)



after a 3-s exposure, there were no significant differences between the 1 and 3-s exposure ($p=0.1825$).

Discussion

This study evaluated different types of LCUs and exposure times: one curing laser, one monowave LED and three

polywave LEDs. Thus, it was not unexpected that the five LCUs would not deliver similar irradiances and radiant exposures (Fig. 2 and Table 3). However, the magnitude of the differences was unexpected. There was a threefold difference in power (408–1538 mW), and a sixfold range in the radiant exposure delivered (5.4–31.0 J/cm²). Therefore, the first hypothesis that the five LCUs would not deliver the same amount of energy (Joules) during light-curing was accepted. Unfortunately, many dentists do not recognize how large these differences are, and many use the same exposure time to photo-cure everything [2, 36, 37].

The second hypothesis that the combined effects of the light from the LCUs and the exothermic reaction would not produce the same temperature increase at the bottom of the three RBCs was accepted. In the present study, the PinkWave used for 10 s caused a significant increase in the temperature at the bottom of the RBCs during photo-activation (Fig. 4). This can be attributed to the higher amount of energy delivered and the different wavelengths emitted by this LCU. The spectral analysis reported in Fig. 2 shows the four wavelength bands from the PinkWave: of note, one wavelength band had an emission peak at 631 nm and another was at 860 nm in the near-infrared region. Light in these regions can cause a heating effect. Figure 3 shows the transmission spectrum (mW/nm) from the PinkWave and Valo Grand through the empty molds and through the molds filled with each RBC. Note that for the PinkWave, there was a significant attenuation of the violet light at 410 nm (λ_1) and the blue light at 471 nm (λ_2) when light passed through the RBCs, which cannot be seen for the other two bands wavelengths with peaks at 631 nm (λ_3) and 860 nm (λ_4). Thus, Fig. 3 shows that most of the red and near-infrared light penetrated through the RBC. This explains why the reduction (%) in power from the Pinkwave (Table 2) was much less than the other LCUs. This infrared radiation from the PinkWave is likely responsible for the larger increase in temperature observed when this LCU was used (Table 4).

When analyzing the Logarithmic Regression for the RBCs temperature rise recordings for Power and Energy (Fig. 5), only the Energy (Joules) delivered had a significant positive correlation ($R^2=0.827$ for Filtek, $R^2=0.763$ for Tetric Evoceram and $R^2=0.721$ for Transcend) with the temperature rise in the RBCs. The results from previous studies support that it is the radiant energy that mainly determines temperature rise and not the irradiance [18]. The greater the amount of energy delivered, the greater the temperature rise. In contrast, no correlation was found between the Power (Watts) and the Temperature (°C). The greater the amount of energy delivered, the greater the temperature rise. Thus, despite delivering the highest power (1,538 mW) and the highest irradiance (5,441 mW/cm²) to the RBCs (Table 3), using the Monet Laser produced the smallest temperature increase. Since the energy delivered is related

to the exposure time, the short, 1-s exposure delivered the lowest low radiant exposure values (5.4 J/cm²) when the Monet Laser was used. This likely explained why the Monet Laser produced the lowest temperature increase in the RBCs. However, this was likely because the RBCs were not as well photo-activated. Of note, the exothermic temperature rises (Fig. 6) when the Monet laser was used were also low probably because there was less polymerization of the RBCs. This is supported by the observation that the Monet Laser used for 1 s produced the lowest hardness values in the RBCs (Table 6). Thus, photo-curing most RBCs for 1 or 3 s does not appear advisable because, in addition to the observation that less energy was delivered when the LCUs were used for shorter times, the polymerization shrinkage forces may develop more rapidly [38]. This may cause increased debonding between the tooth and the RBC to occur. Therefore, clinicians should only use a fast-curing protocol with RBCs that use high-yielding photoinitiators and that have been specifically designed to be photo-cured in 1 to 3 s [24, 28].

The samples were made in identical 2 mm thick Delrin rings, and this thickness did not exceed the manufacturer's instructions for the RBCs. The specimens were weighed to verify that the RBCs in each group were almost identical, and there was only ± 0.005 g (4%) difference in the weight of the RBCs in each group. Thus, any differences in the temperature could only be attributed to the light or to the RBC, and not to any differences in the amount of RBC in the specimens. The decision to use a block of cured RBC was made to provide reflective and thermal backgrounds similar to the cavity floor instead of using white filter paper or a glass slab. Table 4 shows that the choice of RBC affected the temperature rise. Thus, the third hypothesis that there would be no differences in the exothermic temperature rise produced by different RBCs was rejected. Due to the COVID pandemic, the experimental RBC codenamed Transcend has not yet been released to the public, and this is the first report about this experimental RBC from Ultradent. Although some studies show that fillers are chemically inert and do not affect the temperature rise [21] and that there is a high correlation between matrix ratio and temperature rise [39], the highest temperature rise occurred in Transcend UB, regardless of the exposure mode used, even though the manufacturer claims that Transcend had the highest filler content (77.5% per weight—Table 1) among the RBCs tested. This can be explained by the greater translucency (Table 2) of the experimental RBC, Transcend, which allows more light to pass through the RBC. This results in a greater temperature rise [40] at the bottom and better photo-activation at the bottom (Table 6) of this RBC, but this also produces more exothermic heat from the more complete polymerization reaction (Table 4 and Fig. 6).

If the same exposure time is used, the LCU that delivers a high irradiance can cause a high thermal transfer and increase the risk of pulpal damage [41]. When the irradiance is the same, the longer the exposure time, the greater radiant exposure delivered. Consequently, there is also a greater risk of pulpal damage. Thus, it is important to know the exposure time and the radiant exposure received by the specimens. Unfortunately, most contemporary research publications lack an adequate description of the light received by the RBC specimens [36]. Despite these limitations, previous studies have reported that temperature increases of 5.5°C or more in the pulp can lead to irreversible pulp damage [10, 42]. The present study found that the combination of the light and the exothermic reaction produced an increase in the temperature at the bottom of all three RBCs as they photo-cured that was greater than 5.5°C. Thus, all the RBCs could potentially cause some thermal damage to the pulp when they were photo-cured. However, hopefully, pulpal damage should not happen because the dentin between the RBC and the pulp is an excellent thermal insulator [43]. Reducing the exposure time or the irradiance may reduce the risk of tissue damage, since less energy is delivered. However, Tables 2 and 6 show this can adversely affect the mechanical properties of the RBC [22]. Therefore, it seems preferable to use a 10-s exposure time from a conventional LCU to deliver an adequate amount of energy, produce an adequately cured RBC, and an acceptable temperature rise [18].

Figure 1 and Table 4 show that the photo-curing reaction is exothermic, and this exothermic component is RBC-dependent [16]. Thus, the temperature increase is a cumulative result of this exothermic reaction and the exposure to light from the LCU. In contrast, for the post-cured RBCs (T3 in Fig. 1 and Table 4), the temperature increase was only a result of the effect of the light from the LCU [16]. Therefore, the fourth hypothesis that this exothermic heat contribution to the temperature increase would be less than 5.5°C [10] was rejected. Except for these groups: Transcend UB + Monet used for 1 s, Filtek Universal A2 + Monet used for 1 s, Tetric Evoceram A2 + Monet used for 1 s Tetric Evoceram A2 + PC 10 s, all the other combinations of LCU and RBC produced temperature increases that were greater than the 5.5°C threshold (Fig. 6). Transcend generated the highest temperature values using the other 4 LCUs (Table 4) and consistently had the greatest exothermic temperature rise (Fig. 6). The reader can easily test the results by placing some RBC on the back of the hand and then light-curing the RBC. The RBC gets hot. When this is repeated using the cured RBC, the temperature rise is less.

According to all the manufacturers' instructions, all the exposure times used in the study should have adequately photo-activated the 2 mm thick specimens of all the RBCs tested. Transcend was the most transparent RBC (Table 2), and there were no significant differences in the VH between

the top and bottom surfaces (Table 6). After the RBCs had received three repeated exposures, the bottom:top hardness ratios of Transcend were 0.90 or greater using four of the five LCUs. However, even when the Monet was used three times, for a total of 9 s, the bottom:top ratio was only 0.84, and it was only 0.65 when three 1-s exposures were used with the Monet. This may occur because the extent of polymerization has an exponential relationship with the amount of transmitted light received by the RBC [44]. Since there was so much more light at the bottom of the RBC, the RBC was well photo-activated at the bottom. Finally, when analyzing the LCUs, regardless of the RBC used and even after three repeated exposures, the Monet Laser produced the lowest VH values in the RBCs (Fig. 7 and Table 6). Although the Monet Laser delivered a high irradiance of 5,441 mW/cm² at 451 nm, the radiant exposure delivered to the RBCs in the 1-s exposures was only 5.4 J/cm². This was less than from the other LCUs (Table 3). This 2 mm increment of RBC should receive approximately 16 J/cm² of radiant exposure [45]. Thus, it is not surprising that when the Monet was used for 1 s, the Vickers Hardness values were low. When comparing the bottom:top VH values from the top and bottom of the RBCs, there were significant differences between the surfaces for Filtek Universal and Tetric Evoceram ($p=0.0015$) despite the low difference between the bottom and bottom values (Table 3). When the VH values at the bottom for each RBC were compared against the LCU that produced the highest value at the top for that specific RBC, the differences in the bottom:top ratios became even more apparent (Table 6). Thus, because not all of the LCUs tested produced the same hardness values at the top and bottom of the RBCs, the fifth hypothesis of the study was rejected. Table 6 also highlights the importance of using the highest value reached at the top surface under any condition for that RBC when determining the overall bottom:top ratios.

The clinicians should be aware that the choice of the LCU or RBC can affect the temperature rise of the bottom of RBCs by the energy delivered from the LCU (Fig. 5) and that there can be a significant exothermic contribution from the RBC itself (Fig. 6). This becomes more important when placing restorations in children with deep cavities because the amount of thermal transfer to the pulp is affected by the remaining dentin thickness [46]; the thinner the thickness of dentin remaining, the greater the thermal transfer. Therefore, to prevent irreversible pulpal damage [10], it is recommended to blow a stream of air over the tooth during exposure [13] and to use a cavity liner [47].

Although this was a well-controlled study using known volumes of RBC exposed to well-defined amounts of light, it is important to note that the study did not consider other factors that could affect the temperature rise. Future in vitro or in vivo studies should examine the temperature

rise in teeth, the effect of dentin thickness [21], and the consequences of different pulpal fluid flow rates [48]. In addition, the impact of other LCUs and exposure times on the mechanical properties of other RBCs should be studied and reported.

Conclusion

Dentists should be aware that the choice of LCU, the exposure time, and the exothermic contribution from the RBC will affect the temperature rise and hardness values. Within the limitations of this in vitro study, it was concluded that: (1) the energies delivered (J) from the five LCUs were not the same, and different LCUs produced different changes in the temperature as the RBC is photo-activated; (2) the temperature rise is related to the amount of energy delivered and not to the power or the irradiance from the LCU; (3) the combined effect of the light from the LCU and the exothermic reaction of the RBC produced an increase in the temperature that was greater than 5.5°C. The PinkWave caused a significant increase in the temperature of the RBC due to the amount of energy delivered and the energy delivered in the near-infrared region. The Monet Laser used for 1 s delivered the lowest radiant exposure and produced the smallest temperature rise and lowest Vickers hardness values; (4) the translucency of RBCs affects the temperature rise and hardness.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10266-022-00745-1>.

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Declaration

Conflict of interest The authors declare that there is no conflict of interest in this study.

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