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RESEARCH ARTICLE

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In-vitro pulpal temperature increases when photo-curing bulk-fill resin-based composites using laser or light-emitting diode light curing units

Cristiane Maucoski DDS, MS[1,2] | Richard Bengt Price BDS, DDS, MS, PhD[2] | Braden Sullivan BSc[2] | Juliana Anany Gonzales Guarneri DDS, MS[1] | Bruno Gusso MS[1] | Cesar Augusto Galvão Arrais DDS, MS, PhD[1]

[1]Department of Restorative Dentistry, State University of Ponta Grossa, Ponta Grossa, Parana, Brazil

[2]Department of Dental Clinical Sciences, Faculty of Dentistry, Dalhousie University, Halifax, Nova Scotia, Canada

Correspondence
Richard Bengt Price, 5981 University Ave, Halifax, Nova Scotia B3H 3J5, Canada.
Email: rbprice@dal.ca

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Abstract

Objective: To evaluate the in vitro pulpal temperature rise (ΔT) within the pulp chamber when low- and high-viscosity bulk-fill resin composites are photo-cured using laser or contemporary light curing units (LCUs).

Materials and Methods: The light output from five LCUs was measured. Non-retentive Class I and V cavities were prepared in one upper molar. Two T-type thermocouples were inserted into the pulp chamber. After the PT values reached 32°C under simulated pulp flow (0.026 mL/min), both cavities were restored with: Filtek One Bulk Fill (3 M), Filtek Bulk Fill Flow (3 M), Tetric PowerFill (Ivoclar Vivadent), or Tetric PowerFlow (Ivoclar Vivadent). The tooth was exposed as follows: Monet Laser (1 and 3 s), PowerCure (3 and 20 s), PinkWave (3 and 20 s), Valo X (5 and 20 s) and SmartLite Pro (20 s). The ΔT data were subjected to one-way ANOVA followed by Scheffe's post hoc test.

Results: Monet 1 s (1.9 J) and PinkWave 20 s (30.1 J) delivered the least and the highest amount of energy, respectively. Valo X and PinkWave used for 20 s produced the highest ΔT values (3.4–4.1°C). Monet 1 s, PinkWave 3 s, PowerCure 3 s (except FB-Flow) and Monet 3 s for FB-One and TP-Fill produced the lowest ΔT values (0.9–1.7°C). No significant differences were found among composites.

Conclusions: Short 1- to 3-s exposures produced acceptable temperature rises, regardless of the composite.

Clinical Significance: The energy delivered to the tooth by the LCUs affects the temperature rise inside the pulp. The short 1–3 s exposure times used in this study delivered the least amount of energy and produced a lower temperature rise. However, the RBC may not have received sufficient energy to be adequately photo-cured.

KEYWORDS
dental curing lights, dental pulp, laser, resin-based composite, temperature

1 | INTRODUCTION

To simplify restorative procedures, manufacturers have developed restorative materials, such as bulk-fill resin-based composites (RBCs), that can be placed in thicker (4–5 mm) increments and may be less technique sensitive than conventional RBCs.[1] Compared to the conventional RBCs, these bulk-fill composites save clinical time, produce similar or lower levels of postoperative sensitivity,[2] have greater depth of cure,[3] and have a similar clinical performance to conventional posterior composites that are photo-cured in thinner (1.5–2 mm) increments.[4–6]

During the restorative procedure, the light from the light curing unit (LCU) and the heat released from the exothermic reaction of the RBC[7] can increase the pulp temperature (PT).[8,9] The PT has been reported to be affected by the output from the LCU,[10,11] and increasing the irradiance is thought to produce a greater rise in PT when photo-curing the RBC.[12] The first light-emitting diode (LED) based LCUs were considered to be 'cool' because they delivered a lower irradiance (approximately 240 mW/cm^2) than the quartz tungsten halogen based LCUs (approximately 450–1200 mW/cm^2).[8] Many LED lights now deliver irradiances greater than 2000 mW/cm^2, and some manufacturers claim that exposure times shorter than 5 s may be used to reduce photo-cure RBCs and reduce clinical time.[13] However, such high irradiance values have become a concern due to the potential risk to the soft tissues[14] and the dental pulp.[10,15] Using monkeys, Zach and Cohen in 1965[16] reported that an increase in PT of 5.5°C resulted in pulpal necrosis in 15% of the cases, and a temperature rise (ΔT) of 11°C resulted in pulpal necrosis in 60% of the cases. Therefore, many researchers have set a maximum increase of 5.5°C in the PT to be the acceptable limit.[9,17]

Recently, new LCUs that emit a different emission spectra and powers than conventional LCUs have become commercially available. For example, a blue diode laser LCU that emits a high power and high irradiance[18] over a very narrow band of wavelengths has been introduced (Monet Laser, AMD Lasers, West Jordan, UT, USA). The Monet laser LCU is proposed to be an alternative to light curing using conventional LED lights[19,20] and it emits light with a very narrow wavelength range at a high photon density.[20] The manufacturer claims[18] that the Monet Laser delivers an irradiance of 2000–2400 mW/cm^2, and it can photoactivate RBCs in 1 s exposure because it emits a collimated high irradiance beam of light.[21] Another recently released LCU is the PinkWave (Vista Dental Products, Racine, WI, USA). The manufacturer claims that this LCU has 'Quadwave' technology because it emits four distinct bands of wavelengths. The manufacturer claims[22] that the PinkWave produces an irradiance of 1720 mW/cm^2 in the 3 s exposure mode, and claims it will reduce the shrinkage and increase the depth of cure in the RBC. The Valo X (Ultradent Products, South Jordan, UT, USA) is the third generation of the Valo LCU. This multi-peak LCU has a wider 12.5 mm light tip than the original Valo, or the Valo Grand. The Valo X emits three bands of wavelengths, between 380 and 515 nm, and the manufacturer claims that it produces an irradiance of 1100 in the Standard mode and 2200 mW/cm^2 in the Xtra Power mode.[23] Considering that the output from high-irradiance[10] and broader emission spectrum LCUs[9] may influence the increase in PT, concerns have been raised regarding the temperature increase inside the pulp chamber when the teeth are exposed to light emitted from these high-output LCUs.[24]

The impact of photo-curing bulk-fill RBCs on the temperature within the pulp (PT) chamber has already been investigated.[12,17] However, these PT values are also influenced by the heat produced by the exothermic polymerization of the RBC,[7] and the volume of the RBC.[17] This exotherm may be of concern when using bulk-fill RBCs because a greater volume of RBC is photocured at the same time.[17] Consequently, a new approach combining light curing at a high radiant emittance with a modification of the polymerization mechanism in the RBC has been proposed.[25] This new generation of bulk-fill RBCs use a reversible addition-fragmentation chain transfer polymerization (RAFT) mechanism, and some manufacturers claim that these RBCs can be adequately photo-cured in only 3 s. Although such short exposure times have produced similar viscoelastic behavior and mechanical properties to those achieved when longer exposure times were used,[25,26] there is no information to date regarding the effect on the PT when RAFT bulk fill RBCs are photo-cured. There is also no information currently available about the increase in temperature inside the pulp chamber when bulk-fill composite resins are photo-cured using the new diode laser or the recently introduced higher-power LCUs. Therefore, the present study evaluated the PT rise when cavity preparations were restored with low and high viscosity bulk-fill RBCs, and photo-cured with laser, Quadwave, or contemporary high-power LED LCUs. The null hypotheses were that: (1) there is no difference in the in vitro PT rise caused by 1, 3 or 20 s photo-curing times using laser, Quadwave, or contemporary high-power LED LCUs; (2) the differences in viscosity between bulk-fill RBCs will not affect the in-vitro PT rise, regardless of LCU and exposure strategy.

2 | MATERIALS AND METHODS

2.1 | Analysis of the light emitted by the LCUs

One laser diode, one monowave LED, and three multiple-peak high-power LED LCUs (Figure 1) were used (Table 1). The spectral radiant powers from the LCUs were measured using a fiberoptic spectroradiometer (Flame-T, Ocean Insight, Orlando, FL, USA) connected to a 6-inch diameter integrating sphere (Labsphere, North Sutton, NH,

FIGURE 1 Five light curing units used in the study.

TABLE 1 Light curing units (LCUs) information provided by the manufacturers about their LCUs.

Light curing unit	Serial number	Manufacturer	Type	Irradiance (mW/cm^2)	Mode tested
SmartLite Pro	H00466	Dentsply Sirona, Charlotte, NC, USA	Monowave LED	1200	2 × 10 s (Standard)
PinkWave	00380H	Vista Dental Products, Racine, WI, USA	Polywave LED	>1515 >1720	20 s (Standard) 3 s (Boost)
PowerCure	1,428,005,297	Ivoclar Vivadent, Schaan, Liechtenstein	Polywave LED	1200 3050	20 s (High) 3 s (3 s Cure)
Monet Laser	00249	AMD Lasers, West Jordan, UT, USA	Laser	2000–2400	1 s 3 × 1 s
Valo X	00249	Ultradent Jordan, UT, USA	Polywave LED	1100 2200	2 × 10 s (Standard) 5 s (Xtra)

FIGURE 2 Radiograph image to verify the position of the thermocouples and dentin thickness.

USA) that had been previously calibrated using an internal NIST referenced calibration lamp (ICS-600, Labsphere). The tip from each LCU was positioned at the entrance of the sphere to capture all the light emitted from the LCU at the 0 mm distance. The light output was recorded using OceanView software (Ocean Insight, Orlando, FL, USA), which provided the total emitted power and the spectral radiant power. The power was multiplied by the exposure time to provide the energy (J) delivered to the tooth by each LCU. To determine the radiant exitance from each LCU, the internal diameter of each LCU tip was measured using a digital caliper (Mitutoyo, Canada Inc, Mississauga, ON, Canada), and the optical emission area of the tip of each LCU was calculated. This value was divided into the power (W) to obtain the total radiant exitance (mW/cm^2) from the LCU for each exposure mode.

2.2 | In vitro temperature analysis

This study was approved by the local Ethics Board (#2021–5703). The study used one healthy extracted maxillary molar from the University Tooth Bank for all the experiments. The inclusion criteria were that the molar tooth had to be intact and unrestored. An occlusal, non-retentive, Class I (3-mm wide, 4-mm deep and 5-mm long) and a buccal, non-retentive, Class V cavity (2-mm wide, 2-mm deep and 5-mm long) with divergent walls were made using a high-speed carbide bur. The cavity dimensions were verified using a William's periodontal probe. Approximately 1 mm of dentin was left on the pulpal wall of the Class I and V cavities. To verify the thickness of the remaining dentin and the position of the thermocouples, radiographs were taken and measurements were made from these radiographs (Figure 2). The Class I and V cavities in the molar tooth are shown in Figure 3. The cavity walls were polished using Enhance polisher (Dentsply Sirona) so that there was minimal mechanical retention to the cavity wall and the RBC could be easily removed. The tooth roots were sectioned 4 mm below the cement-enamel junction and were enlarged with Gates Glidden drills (Dentsply Sirona, York, PA, USA).

Two 0.011″ diameter ultra-fast response T-type thermocouples (IT-23 Physitemp Instruments, Clifton, NJ, USA) were placed in the pulp chamber through the enlarged roots, one close to the pulp horn and the other close to the Class V cavity. The molar tooth was attached to an acrylic plate to simulate the effect of using a rubber dam and clamp.[24] To simulate the conditions in the oral cavity, the tooth was inserted in a warm water bath (Isotemp 2150 Immersion Circulator, Fisher Scientific Inc., Pittsburgh, PA, USA) up to the cemento-enamel junction. Temperature measurements inside the pulp chamber were made under controlled physiological simulation at a basal pulp temperature of approximately 32°C, which is thought to simulate the baseline temperature of the tooth after etching and rinsing.[27] A tube was placed into the mesial root and connected to a peristaltic pump (Peristaltic Pump P-1, Pharmacia Fine Chemicals, Uppsala, Sweden). The water flow rate through the tube into the pulp chamber was set to 0.026 mL/min.[24,28,29] A third thermocouple was placed in the water bath to measure the water temperature.

A temperature acquisition software (TCChart, Nomadics Inc., Stillwater, OK, USA) was used to record the temperature every 0.05 s before, during and after the restoring procedures. A schematic illustrating how the temperature was recorded is shown in Figure 4. So that the restoration could be removed after light curing, no bonding procedure was performed. Instead, a very thin coating of Vaseline (Covidien, Mansfield, MA, USA) was applied to the cavity, and a piece of dental floss was inserted into the RBC before photo-curing. After reaching the baseline temperature of 32°C, the Class I cavity was

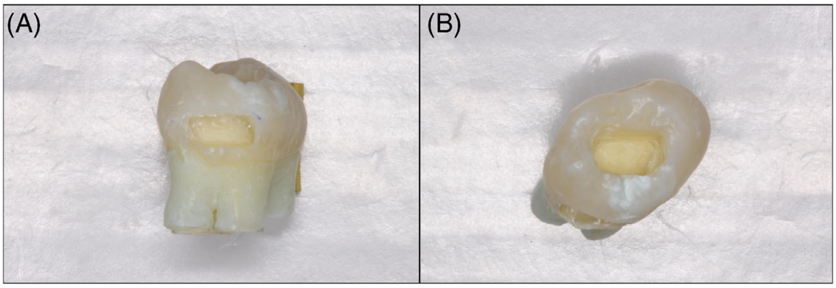

FIGURE 3 Class I and V cavities in the molar tooth.

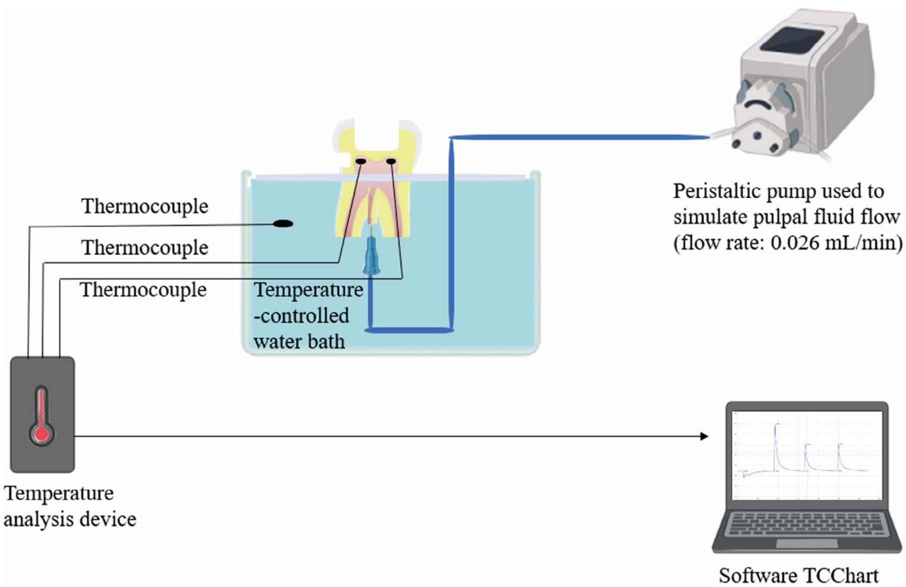

FIGURE 4 Schematic illustrating how the temperature was recorded.

TABLE 2 Resin-based composites.

RBC	Lot number	Type	Manufacturer	Shade
Filtek Bulk Fill Flowable	NF23205	Low viscosity	3 M Oral Care, St Paul, MN, USA	A2
Filtek One Bulk Fill	NC44145 NE63556	High viscosity	3 M Oral Care, St Paul, MN, USA	A2
Tetric PowerFlow	Z02X2L Z010KV	Low viscosity	Ivoclar Vivadent, Schaan, Liechtenstein	IVA
Tetric PowerFill	Z02PCM Z033N3	High viscosity	Ivoclar Vivadent, Schaan, Liechtenstein	IVA

filled up to a depth of 4 mm using one of the following RBCs (Table 2): Filtek One Bulk Fill (FB-One; Shade A2; 3M, St. Paul, MN, USA), Filtek Bulk Fill Flowable (FB-Flow; Shade A2; 3M), Tetric PowerFill (TP-Fill; Shade IVA; Ivoclar Vivadent, Schaan, Liechtenstein), or Tetric PowerFlow (TP-Flow; Shade IVA; Ivoclar Vivadent). TP-Fill and TP-Flow use the RAFT polymerization mechanism. FB-One and FB-Flow use RAFT related technology. The tip of the curing light was positioned at 0 mm from the cusp tip, and the bulk-fill RBCs were exposed to the light-curing conditions reported in Table 1. The same procedure was performed for the Class V cavity, where the LCU tip was placed on the buccal surface, except that the Class V cavity was only 2 mm deep. Figure S1 describes the design of the experiment.

2.3 | Statistical analysis

Since some manufacturers market the bulk-fill RBC and LCU (Ivoclar Vivadent) as a restorative system, the factorial design of the study consisted of one independent variable (Bulk-fill RBC/LCU), and one dependent variable (temperature). The factorial scheme resulted in 72 experimental groups, with five repetitions for each ($n = 5$). The ΔT values for Class I and Class V cavities were first subjected to a one-way analysis of variance (ANOVA) test followed by Scheffe's post-hoc tests. Statistical testing and post-hoc analyses were conducted at 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 the Energy (Joules) delivered from the LCUs to the RBCs.

TABLE 3 Peak wavelengths, tip diameter, tip area, power, energy delivered, radiant exitance (tip irradiance) and radiant exposure from the nine exposure conditions.

				Power (mW)		Energy (J)		
Light and exposure time	Peak wavelengths (nm)	Tip diameter (mm)	Tip area (cm^2)	Mean	SD		Radiant exitance (mW/cm^2)	Radiant exposure (J/cm^2)
Monet 1 s	451	12.8	1.29	1933	3.7	1.9	1502	1.5
PowerCure 3 s	408 and 451	8.3	0.54	1525	3.2	4.6	2818	8.5
PinkWave 3 s	410, 471, 631 and 860	11.9	1.11	1874	6.1	5.6	1685	5.1
Monet 3 s	451	12.8	1.29	1933	3.7	5.8	1502	4.5
PowerCure 20 s	408 and 451	8.3	0.54	572	1.3	11.4	1057	21.1
Valo X 5 s	393, 445 and 458	12.5	1.23	2579	9.7	12.9	2102	10.5
SmartLite Pro 20 s	462	10.3	0.83	886	0.9	17.7	1064	21.3
Valo X 20 s	393, 445 and 458	12.5	1.23	1277	6.5	25.5	1041	20.8
PinkWave 20 s	410, 471, 631 and 860	11.9	1.11	1505	6	30.1	1353	27.1

Note: Exposure conditions ranked from the lowest to highest amount of energy (J) delivered.

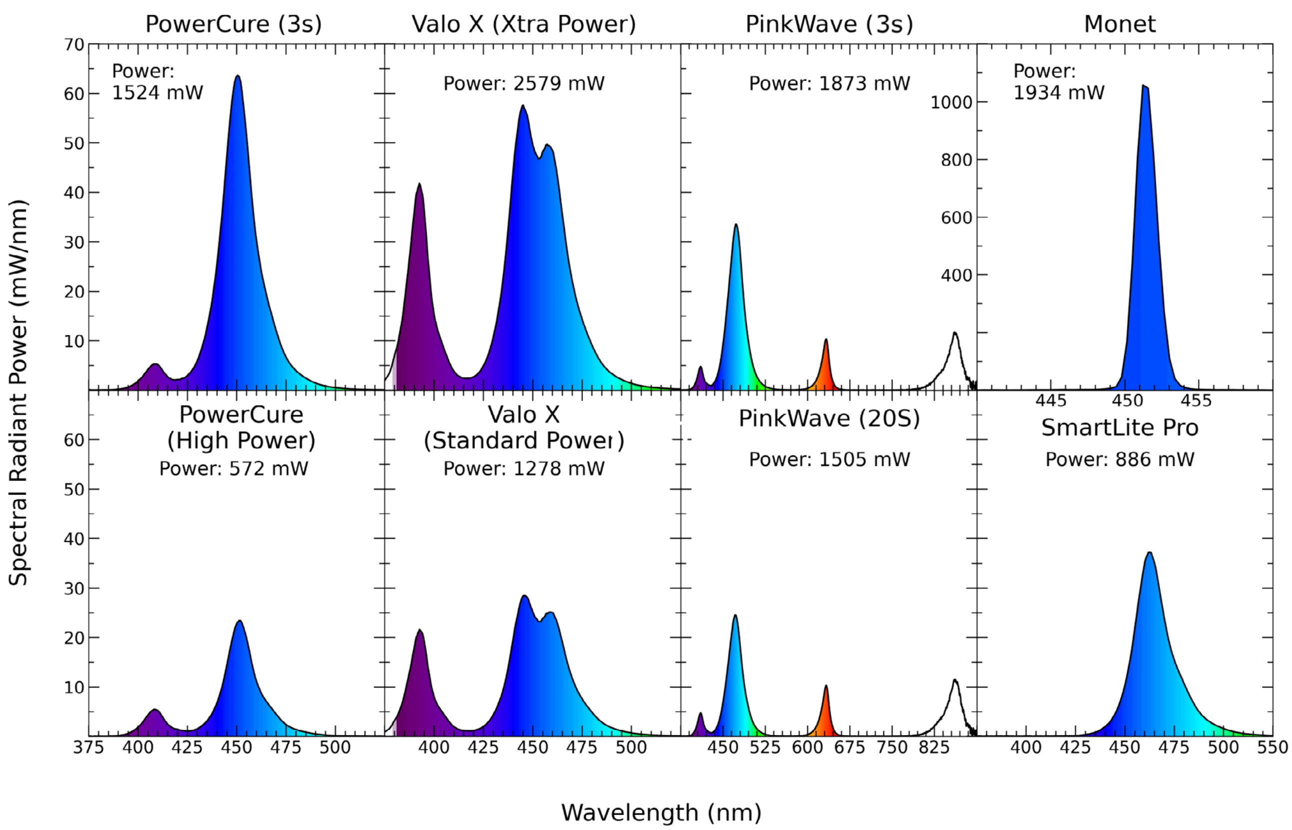

FIGURE 5 Emission spectra and power (mW) from the light-emitting diode light curing units (LCUs) and from the Laser LCU. Different wavelength and spectral radiant power scales are used for the Monet Laser compared to the other LCUs. The PinkWave wavelength scale is also different from the other LCUs because it delivers a wider range of wavelengths.

3 | RESULTS

3.1 | Analysis of the light emitted by the LCUs

Table 3 reports the tip diameter (mm), power (mW), energy (J), radiant exitance or irradiance (mW/cm^2), and radiant exposure (J/cm^2) emitted by each exposure condition in the wavelength range between 350 and 900 nm for PinkWave and between 350 and 550 nm for the other LCUs. The Valo X used for 5 s emitted the highest power (2579 ± 9.7 mW). The PowerCure used for 20 s emitted the lowest power (572 ± 1.3 mW), but it still delivered 11.4 J in a 20 s exposure. The Monet used for 1 s delivered the least amount of energy (1.9 J), and

TABLE 4 Temperature rise (Δ*T*) recorded for the Class I cavity ranked from the greatest to least temperature rise.

		Temperature rise (Δ*T*—°C)					
		Probe in the Class 1 location			Probe in the Class 5 location		
Exposure condition	RBC	Mean	SD		Mean	SD	
Valo X 20 s	Filtek Bulk Fill Flow	4.1	0.1	A	4.6	0.2	A
Valo X 20 s	Tetric PowerFill	4.1	0.3	A	3.8	0.2	ABC
Valo X 20 s	Tetric PowerFlow	3.9	0.1	AB	4.2	0.4	AB
PinkWave 20 s	Filtek Bulk Fill Flow	3.8	0.3	AB	4.6	0.4	A
Valo X 20 s	Filtek One	3.8	0.4	AB	3.7	0.2	ABCD
PinkWave 20 s	Tetric PowerFill	3.7	0.5	ABC	3.7	0.5	ABCD
PinkWave 20 s	Tetric PowerFlow	3.5	0.1	ABCD	4.2	0.2	AB
PinkWave 20 s	Filtek One	3.4	0.4	ABCDE	3.6	0.3	ABCD
SmartLite Pro20 s	Filtek Bulk Fill Flow	3.1	0.1	BCDEF	3.4	0.2	BCDE
SmartLite Pro20 s	Tetric PowerFill	2.9	0.3	CDEFG	2.9	0.3	CDEFG
SmartLite Pro20 s	Tetric PowerFlow	2.9	0.1	CDEFG	3.2	0.1	CDEF
SmartLite Pro20 s	Filtek One	2.7	0.1	DEFGH	2.7	0.3	DEFG
PowerCure 20 s	Filtek Bulk Fill Flow	2.7	0.0	DEFGH	2.8	0.2	DEFG
Valo X 5 s	Filtek Bulk Fill Flow	2.6	0.2	EFGHI	2.6	0.1	EFGH
PowerCure 20 s	Tetric PowerFlow	2.5	0.1	FGHIJ	2.5	0.2	EFGH
Valo X 5 s	Tetric PowerFlow	2.5	0.2	FGHIJ	2.4	0.1	EFGHI
PowerCure 20 s	Tetric PowerFill	2.4	0.3	FGHIJ	2.3	0.3	FGHIJ
PowerCure 20 s	Filtek One	2.3	0.2	FGHIJK	2.2	0.2	FGHIJKL
Valo X 5 s	Filtek One	2.2	0.1	GHIJKL	1.9	0.5	GHIJKLM
Valo X 5 s	Tetric PowerFill	2.2	0.1	GHIJKL	2.2	0.1	FGHIJK
Monet 3 s	Filtek Bulk Fill Flow	2.0	0.2	HIJKLM	2.1	0.2	GHIJKL
Monet 3 s	Tetric PowerFlow	1.9	0.1	HIJKLMN	2.0	0.0	GHIJKLM
PowerCure 3 s	Filtek Bulk Fill Flow	1.8	0.1	IJKLMNO	1.7	0.2	HIJKLMN
PowerCure 3 s	Tetric PowerFlow	1.7	0.1	IJKLMNOP	1.6	0.0	HIJKLMN
PinkWave 3 s	Filtek Bulk Fill Flow	1.7	0.1	JKLMNOP	1.7	0.1	HIJKLMN
Monet 3 s	Tetric PowerFill	1.6	0.1	KLMNOP	1.7	0.1	HIJKLMN
PinkWave 3 s	Tetric PowerFlow	1.5	0.1	KLMNOP	1.9	0.2	GHIJKLMN
Monet 3 s	Filtek One	1.5	0.0	KLMNOP	1.5	0.1	IJKLMN
PowerCure 3 s	Tetric PowerFill	1.4	0.1	LMNOP	1.4	0.1	IJKLMN
PinkWave 3 s	Tetric PowerFill	1.4	0.0	LMNOP	1.3	0.1	JKLMN
PowerCure 3 s	Filtek One	1.4	0.1	MNOP	1.2	0.1	KLMN
PinkWave 3 s	Filtek One	1.2	0.2	MNOP	1.3	0.1	KLMN
Monet 1 s	Filtek Bulk Fill Flow	1.2	0.0	MNOP	1.2	0.1	LMN
Monet 1 s	Tetric PowerFill	1.1	0.1	NOP	1.1	0.1	MN
Monet 1 s	Tetric PowerFlow	1.0	0.0	OP	1.1	0.1	MN
Monet 1 s	Filtek One	0.9	0.2	P	0.9	0.2	N

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

the PinkWave used for 20 s delivered the greatest amount of energy (30.1 J).

Table 3 and Figure 5 show the peak wavelengths (nm) and the spectral radiant power from the LCUs on each setting. The Monet Laser and SmartLite Pro both delivered one single emission peak. However, the Monet Laser emitted a very narrow band of wavelengths with a peak centered at 451 nm compared to SmartLite Pro that had a broader emission spectrum with a peak centered at 462 nm. The PowerCure, Valo X, and PinkWave were multi-peak broadband LED LCU lights. The PowerCure delivered two wavelength

TABLE 5 Temperature rise (Δ*T*) recorded for the Class V cavity ranked from the greatest to least temperature rise.

		Temperature rise (Δ*T*—°C)					
		Probe in the Class 1 location			Probe in the Class 5 location		
Exposure condition	RBC	Mean	SD		Mean	SD	
PowerCure 20 s	Filtek Bulk Fill Flow	0.9	0.1	ABCD	4.0	0.3	A
PowerCure 20 s	Tetric PowerFlow	1.0	0.0	ABCD	4.0	0.4	A
PinkWave 20 s	Filtek Bulk Fill Flow	1.0	0.1	ABC	3.6	0.2	AB
Valo X 20 s	Filtek Bulk Fill Flow	1.1	0.1	A	3.5	0.1	ABC
SmartLite Pro 20 s	Filtek Bulk Fill Flow	0.9	0.1	ABCDE	3.3	0.1	ABCD
PinkWave 20 s	Tetric PowerFlow	0.9	0.1	ABCD	3.3	0.3	ABCDE
PowerCure 20 s	Tetric PowerFill	0.9	0.0	ABCDE	3.3	0.2	ABCDEF
SmartLite Pro 20 s	Tetric PowerFlow	0.9	0.1	ABCDE	3.1	0.2	BCDEFG
PowerCure 20 s	Filtek One	0.9	0.1	ABCDE	3.0	0.1	BCDEFG
Valo X 20 s	Tetric PowerFlow	1.0	0.0	AB	2.9	0.2	BCDEFGH
Valo X 20 s	Tetric PowerFill	1.1	0.1	A	2.5	0.3	CDEFGHI
Valo X 20 s	Filtek One	1.1	0.1	AB	2.5	0.3	DEFGHI
SmartLite Pro 20 s	Tetric PowerFill	0.9	0.1	ABCDE	2.4	0.1	EFGHI
PinkWave 20 s	Tetric PowerFill	0.7	0.1	BCDEFGH	2.4	0.1	EFGHI
PinkWave 20 s	Filtek One	0.8	0.1	BCDEF	2.4	0.2	FGHI
SmartLite Pro 20 s	Filtek One	0.8	0.1	ABCDE	2.3	0.2	GHI
Valo X 5 s	Filtek Bulk Fill Flow	0.8	0.0	BCDEFG	2.2	0.2	GHI
PowerCure 3 s	Tetric PowerFlow	0.7	0.1	CDEFGHIJK	2.2	0.2	GHI
Valo X 5 s	Tetric PowerFlow	0.7	0.1	BCDEFG	2.1	0.2	GHI
PowerCure 3 s	Filtek Bulk Fill Flow	0.7	0.1	CDEFGHI	2.1	0.2	HIJ
PowerCure 3 s	Tetric PowerFill	0.6	0.1	EFGHIJKLM	2.0	0.1	HIJ
Valo X 5 s	Tetric PowerFill	0.6	0.1	DEFGIJKL	1.9	0.2	IJK
PowerCure 3 s	Filtek One	0.7	0.0	CDEFGHI	1.9	0.2	IJK
Valo X 5 s	Filtek One	0.7	0.1	CDEFGHIJ	1.7	0.1	IJKL
PinkWave 3 s	Filtek Bulk Fill Flow	0.4	0.1	HIJKLM	1.2	0.3	JKLM
PinkWave 3 s	Tetric PowerFlow	0.3	0.0	IJKLM	1.1	0.1	JKLM
PinkWave 3 s	Tetric PowerFill	0.3	0.1	IJKLM	1.1	0.2	KLM
Monet 3 s	Tetric PowerFlow	0.4	0.1	HIJKLM	1.1	0.2	KLM
Monet 3 s	Filtek Bulk Fill Flow	0.4	0.1	GHIJKLM	1.0	0.3	KLM
PinkWave 3 s	Filtek One	0.3	0.1	KLM	1.0	0.0	KLM
Monet 1 s	Tetric PowerFlow	0.3	0.1	LM	0.9	0.1	LM
Monet 3 s	Tetric PowerFill	0.4	0.1	FGHIJKLM	0.9	0.1	LM
Monet 1 s	Filtek Bulk Fill Flow	0.3	0.1	M	0.9	0.1	LM
Monet 1 s	Tetric PowerFill	0.2	0.1	M	0.7	0.2	M
Monet 3 s	Filtek One	0.3	0.1	JKLM	0.6	0.0	M
Monet 1 s	Filtek One	0.2	0.1	M	0.5	0.0	M

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

peaks, one in the violet region (λ1 = 408 nm) and one in the blue region (λ2 = 451 nm) and the Valo X (λ1 = 393 nm; λ2 = 445 nm, and λ3 = 458 nm). The PinkWave LCU emitted four distinct bands of wavelengths, three in the range of visible light (λ1 = 410 nm; λ2 = 471 nm, and λ3 = 631 nm), and one in the invisible near-infrared spectral range/thermal radiation (λ4 = 860 nm).

3.2 | In-vitro temperature analysis

Table 4 reports the Δ*T* produced by the RBCs in the Class I cavity. The Valo X and the PinkWave used for 20 s (between 3.4 and 4.1°C) for all the four RBCs produced the highest Δ*T* values. There were no significant differences between the four RBCs. The Monet for 1 s,

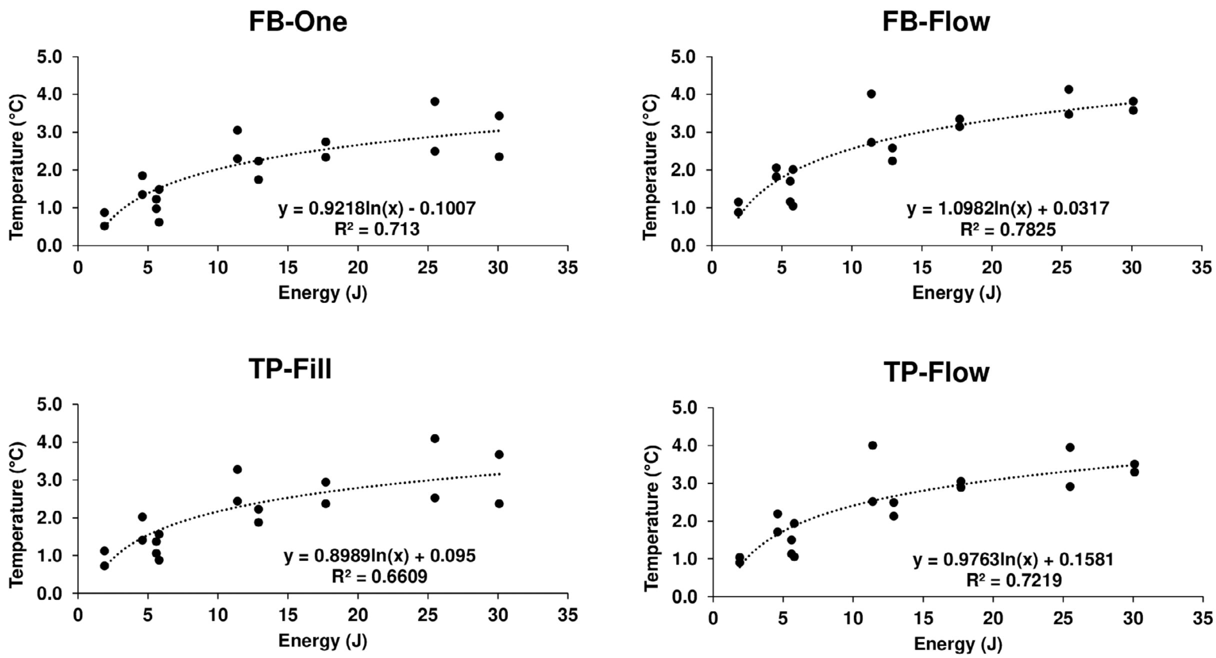

FIGURE 6 Regression analyses for FB-One, FB-Flow, TP-Fill and TP-Flow RBCs temperature rise when examining the relationship between the temperature rise and the total energy (J) delivered from the light curing units.

PinkWave for 3 s, PowerCure for 3 s (except when using FB-Flow) and the Monet used for 3 s for FB-One and TP-Fill produced the lowest ΔT values (between 0.9 and 1.7°C). A similar pattern in the ΔT values was observed in both thermocouple positions. However, the rank of the ΔT values in the Class I cavity produced by the different LCU/resin composite differed from those observed in the Class V cavity.

Table 5 reports the ΔT for the Class V cavity. When performing Class V restorations, the thermocouple probe that was closest to the Class V cavity reported that the PowerCure used for 20 s (FB-Flow, TP-Flow and TP-Fill), the PinkWave used for 20 s (FB-Flow and TP-Flow), Valo X 20 s (FB-Flow) and SmartLite Pro (FB-Flow) used for 20 s produced the highest ΔT values that were between 3.3 and 4.0°C. However, there were no significant differences between these LCUs. The lowest ΔT values were produced by the Monet when it was used for 1 s, the Monet used for 3 s, and PinkWave used for 3 s for all four RBCs tested (between 0.5 and 1.2°C). Contrary to the ΔT values reported in the Class I cavity where similar patterns in the ΔT values was observed in both thermocouple positions, in the Class V cavity, the thermocouple placed furthest from the axial wall recorded lower ΔT values than the thermocouple placed near the axial wall that was adjacent to the Class V cavity.

Figure 6 shows the results of logarithmic regression analyses of the relationship between the ΔT values (°C) and the Energy (Joules) delivered to the tooth. For all the RBCs, there was a positive correlation between the amount of energy (J) delivered from the LCU and the temperature rise inside the pulp chamber ($R^2 = 0.713$ for FB-One, $R^2 = 0.783$ for FB-Flow, $R^2 = 0.661$ for TP-Fill and $R^2 = 0.722$ for TP-Flow).

4 | DISCUSSION

This study evaluated the PT changes when low and high viscosity bulk-fill RBCs, both having a form of RAFT technology[25,30] were photo-cured in Class I and Class V cavities using laser, Quadwave and contemporary LED LCUs. Most exposure conditions that used longer exposures (up to 20 s) at a lower radiant exitance value caused higher ΔT values inside the pulp chamber than shorter exposures at higher radiant exitance values because less energy was delivered. More specifically, when the Valo X LCU and PinkWave were used for 20 s (the longer exposure times) in the Class I cavity produced the highest ΔT values, while the groups that were exposed for 1 or 3 s had the lowest values (Table 4). Therefore, the first hypothesis that there is no difference in the in vitro PT rise caused by 1, 3, or 20 s photo-curing times using laser, Quadwave, or contemporary high-power LED LCUs was rejected. LCUs that emit a wider spectrum of light may produce a greater rise in temperature when compared to narrow-spectrum LED-LCUs.[10] This occurs because the photons in the violet range are at shorter wavelengths and they deliver more energy.[31] This study shows that the impact of the photo-curing on the PT rise is greater at longer exposures[32] because the increase in temperature is closely related to the radiant exposure values delivered to the tooth.[33] Therefore, the Valo X (delivering 1277 mW and 1041 mW/cm^2) used for 20 s delivered approximately 25.5 J and 20.8 J/cm^2. While the higher output mode from this LCU delivered 2102 mW/cm^2, when used for 5 s, it only delivered approximately 12.9 J and 10.5 J/cm^2 (Table 3). This difference in the energy delivered to the tooth explains the higher ΔT values in the groups with the longer exposures than those observed during the shorter exposure times, despite delivering 1933 mW. Although the Monet is a high-powered Class 4 laser, it emits light over a very narrow wavelength range (Figure 5 and Table 3), and when used for 1 s, it delivered the least amount of energy (1.9 J). Consequently, it produced the lowest ΔT values. Such findings reinforce the previous reports that the PT rise is more closely related to the radiant exposure values (J/cm^2) received rather than the irradiance values from the LCU.[27,33]

Of note, the rank of LCUs/RBCs based on the descending order of Δ*T* values in the Class I cavity (Table 4) differed from that observed from the Class V cavity (Table 5). The highest Δ*T* values in Class I restorations were observed during the 20 s exposure to the Valo X and Pinkwave (Table 4), while PowerCure combined with FB-Flow and TP-Flow caused the highest Δ*T* values in the Class V restoration. As described in the Methods section, to simulate a clinical Class V restoration scenario where a rubber dam is used, the molar tooth was fixed in an acrylic plate so that only the crown above the cemento-enamel junction was exposed. This arrangement did not allow some LCUs with larger tip diameters, such as the Valo X (tip diameter of 12.5 mm) or the PinkWave (tip diameter of 11.9 mm), to be centered directly over the Class V cavity. Thus, the PowerCure, which has a smaller diameter than the other LCUs used in this study (Table 3), could be positioned directly over the Class V cavity, and the tip could cover the entire restoration. This position of the LCU tip allowed more direct illumination and a better transfer of light and energy to the restoration.[8] This allowed a greater heat transfer through the RBC and remaining dentin floor to the pulp and resulted in the highest Δ*T* values. In contrast, much of the light from the Valo X and PinkWave was directed over the cusp tip and this resulted in a lower temperature rise. Thus, direct access to the restoration plays an important role in the amount of energy delivered and consequently the temperature rise.

Previous studies have reported that low viscosity composites can cause a higher PT increase than high viscosity RBCs because they have a lower filler content and contain more resin. This increase in the resin content produces more exothermic heat.[17,34–36] Although the FB-Flow and TP-Flow caused the highest PT rise (Δ*T*) used in the Class V cavity (Table 5), overall, there was no significant difference, and the second hypothesis that the differences in viscosity between bulk-fill RBCs will not affect the in-vitro PT rise regardless of LCU and exposure strategy was accepted for these four RAFT associated RBCs. In the present study, the Class I and Class V cavities had approximately 1 mm of dentin on the pulpal wall between the bottom of the cavity and the pulp chamber. Some studies have shown that dentin has an excellent insulation capacity because of its low thermal diffusivity ($\approx 1.87 \times 10^{-3}$ cm^2/s).[37] Therefore, when there is thicker dentin remaining on the cavity floor, a lower PT increase will occur.[38–41] Consequently, when the heat released by the exothermic reaction reached the surface, the remaining dentin on both pulpal and axial walls might have been capable of absorbing that heat and transferring it to the surrounding structure slowly. Thus, any differences in the heat released between the low viscosity and high viscosity RBCs were not detected by the thermocouple after the heat had passed through the remaining dentin. Also, some studies have noticed that the heat produced during photo-curing is more influenced by the choice of LCU rather than by the exothermic reaction of the RBC.[7,42] These two factors could explain why, overall, there were no significant differences in the PT increase in the low viscosity and high viscosity RBCs.

The 20-s exposure using PinkWave caused the highest PT rise (Δ*T*) in the Class I restorations (Table 4) and when FB-Flow and TP-Flow were used in the Class V cavity (Table 5). The PinkWave is a multi-peak LED LCU that delivers infra-red (IR) and red wavelengths of light as well as blue and violet light. The Far Infrared Radiation (FIR) is a subdivision of the IR band that transfers energy as heat that thermoreceptors can feel as radiant heat.[43] Thus, the thermal irradiation from PinkWave, in addition to the relatively high-power output from this LCU (1874 mW), helps to explain why the PinkWave LCU caused one of the highest PT rise values among all groups.

In the present study, the two thermocouples placed inside the pulp chamber of a maxillary molar simultaneously recorded the temperature changes in the pulpal chamber of the Class I and the axial floor of the Class V cavities. The results reported some differences in PT increase when the values recorded by both thermocouples were compared for each cavity and within each exposure condition and RBC. As the light emitted from the LCU hits the surface, part of the light is reflected, part is transmitted, part is scattered, and part is converted into heat.[44] This heat is transferred to and absorbed by the surrounding structures,[41] and a temperature gradient is created in the surrounding structure and pulp tissue.[41] Consequently, when the RBC was placed and photo-cured within the Class V cavity, the temperature values recorded by the thermocouple placed near the axial floor were higher than those recorded by the thermocouple that was located further away from RBC and the axial floor.

The logarithmic regression (Figure 6) examining the effect of the energy (J) on the temperature rise, shows that there was a significant positive correlation between the energy (J) delivered and the PT ($R^2 = 0.713$ for FB-One, $R^2 = 0.783$ for FB-Flow, $R^2 = 0.661$ for TP-Fill and $R^2 = 0.722$ for TP-Flow). Despite the fact that different LCUs were used, the lower the amount of energy delivered, the lower the temperature rise inside the tooth. This agrees with a previous study that showed that the temperature rise was mainly determined by the radiant exposure.[45] The clinician should also be aware that delivering a low radiant exposure will compromise the mechanical properties of the restorations,[46,47] and can increase the material's toxicity.[47]

For this in vitro study, the fluid flow through the pulp was adjusted to a flow rate of 0.026 mL/min based on previous studies.[24,28,29] After comparing in vitro and in vivo models regarding pulp temperature rise, a previous study found that PT rise in the in vitro model was close to those exhibited by the in vivo model.[48] The pulp fluid flow can significantly reduce the PT increase,[49,50] which is also influenced by the pulp flow rate.[50] Therefore, the impact of the evaluated LCUs, radiant exitance (irradiance), exposure time, and resin composites on the PT rise may be different if the pulp flow rate changes.

However, when evaluating the effects of low flow rates of 0.0042 mL/min, 0.028 or 0.07 mL/min, which were close to the one used in the study, a previous in vitro study found little effect on pulp temperature.[11] Thus, it is reasonable to expect such LCUs and RBCs would cause in vivo temperature rise values similar to those observed in the current study.

Although significant increases in the PT values were noticed, all exposure modes produced acceptable temperature rises within the pulp chamber of this in vitro tooth because the PT rise values were lower than the threshold of 5.5°C.[16] The extent of the rise in PT was related to the energy delivered and not to the radiant exitance (irradiance) values delivered by the LCUs. An in vivo study performed in humans reported that short-exposures delivering 10,000 mW/cm^2, caused an increased expression of some precursors of the inflammatory response, such as Interleukin-1β, in the pulp tissue, compared to the expression of this marker when lower radiant exitance values that were below 24.6 J/cm^2 were delivered for a longer time. However, when 73.8 J/cm^2 was delivered in 60 s at 1231 mW/cm^2 the blood vessels were dilated and congested.[51] The authors attributed the outcomes to the higher rate of temperature rise observed when 10,000 mW/cm^2 was delivered for 1 or 2 s.[51] This radiant exitance and the radiant exposure values were 3–10 times greater than the maximum radiant exitance (2818 mW/cm^2) and radiant exposure values (27.1 J/cm^2) used in the present study (Table 3) and highlight why it is important to report the radiant exitance and energy delivered, rather than uses ill-defined terms such as 'high irradiance, or a high power LCU'.

The Class I and V restorations were made in only one maxillary molar. Therefore, the current temperature increases should not be expected in teeth with smaller crown volumes, such as premolars and incisors or when using more RBC in a larger cavity. But the observation that the more energy that is delivered, the greater the temperature rise should still be valid (Figure 6). The Class I and V cavity preparations left approximately 1 mm of dentin at the floor of the cavity, if there is a thinner amount of dentin on the cavity floor, this may result in different increases in PT. Furthermore, the study was designed to only examine RAFT modified bulk-fill RBCs, that were photo-cured in one 2 or 4-mm thick increments. Therefore, the current finding should not be expected when a cavity preparation is restored with conventional RBCs using the incremental technique.

5 | CONCLUSIONS

Within the limitations of this in vitro study, it was concluded that:

1. Fast photo-polymerization in 1–3 s using radiant exitances that were below 3000 mW/cm^2 did not produce unacceptable temperature rises within the pulp chamber because amount of energy delivered to the tooth in 1–3 s was less than 6 J.
2. The in-vitro PT rise is related to the amount of energy delivered to the tooth and the ability of the LCU tip to be positioned directly over the restoration.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Cristiane Maucoski https://orcid.org/0000-0001-7159-2400
Richard Bengt Price https://orcid.org/0000-0001-6479-1436
Braden Sullivan https://orcid.org/0000-0002-3328-7365
Juliana Anany Gonzales Guarneri https://orcid.org/0000-0003-2764-0748
Bruno Gusso https://orcid.org/0000-0003-1283-1963
Cesar Augusto Galvão Arrais https://orcid.org/0000-0003-3432-5009

REFERENCES

1. Chesterman J, Jowett A, Gallacher A, Nixon P. Bulk-fill resin-based composite restorative materials: a review. *Br Dent J*. 2017;222(5):337-344.
2. Tardem C, Albuquerque EG, Lopes LS, et al. Clinical time and postoperative sensitivity after use of bulk-fill (syringe and capsule) vs. incremental filling composites: a randomized clinical trial. *Braz Oral Res*. 2019;33:e089.
3. Van Ende A, De Munck J, Lise DP, Van Meerbeek B. Bulk-fill composites: a review of the current literature. *J Adhes Dent*. 2017;19(2):95-109.
4. Veloso SRM, Lemos CAA, de Moraes SLD, do Egito Vasconcelos BC, Pellizzer EP, de Melo Monteiro GQ. Clinical performance of bulk-fill and conventional resin composite restorations in posterior teeth: a systematic review and meta-analysis. *Clin Oral Investig*. 2019;23(1):221-233.
5. Tirapelli C. Is the clinical performance of incremental and bulk-fill resin composite different? *Evid Based Dent*. 2022;23(2):84.
6. Arbildo-Vega HI, Lapinska B, Panda S, Lamas-Lara C, Khan AS, Lukomska-Szymanska M. Clinical effectiveness of bulk-fill and conventional resin composite restorations. *Syst Rev Meta-Anal Polym*. 2020;12(8):1786.
7. Balestrino A, Verissimo C, Tantbirojn D, Garcia-Godoy F, Soares CJ, Versluis A. Heat generated during light-curing of restorative composites: effect of curing light, exotherm, and experiment substrate. *Am J Dent*. 2016;29(4):234-240.
8. Rueggeberg FA, Giannini M, Arrais CAG, Price RBT. Light curing in dentistry and clinical implications: a literature review. *Braz Oral Res*. 2017;31(suppl 1):e61.
9. Mouhat M, Stangvaltaite-Mouhat L, Mercer J, Nilsen BW, Ortengren U. Light-curing units used in dentistry: effect of their characteristics on temperature development in teeth. *Dent Mater J*. 2021;40:1177-1188.
10. Mouhat M, Mercer J, Stangvaltaite L, Ortengren U. Light-curing units used in dentistry: factors associated with heat development-potential risk for patients. *Clin Oral Investig*. 2017;21(5):1687-1696.

11. Park SH, Roulet JF, Heintze SD. Parameters influencing increase in pulp chamber temperature with light-curing devices: curing lights and pulpal flow rates. *Oper Dent*. 2010;35(3):353-361.
12. Wang WJ, Grymak A, Waddell JN, Choi JJE. The effect of light curing intensity on bulk-fill composite resins: heat generation and chemomechanical properties. *Biomater Investig Dent*. 2021;8(1):137-151.
13. Almeida R, Manarte-Monteiro P, Domingues J, et al. High-power LED units currently available for dental resin-based materials-a review. *Polymers*. 2021;13(13).
14. Maucoski C, Zarpellon DC, Dos Santos FA, et al. Analysis of temperature increase in swine gingiva after exposure to a Polywave((R)) LED light curing unit. *Dent Mater*. 2017;33(11):1266-1273.
15. Kim MJ, Kim RJ, Ferracane J, Lee IB. Thermographic analysis of the effect of composite type, layering method, and curing light on the temperature rise of photo-cured composites in tooth cavities. *Dent Mater*. 2017;33(10):e373-e383.
16. Zach L, Cohen G. Pulp response to externally applied heat. *Oral Surg Oral Med Oral Pathol*. 1965;19(4):515-530.
17. Lempel E, Ori Z, Kincses D, Lovasz BV, Kunsagi-Mate S, Szalma J. Degree of conversion and in vitro temperature rise of pulp chamber during polymerization of flowable and sculptable conventional, bulk-fill and short-fibre reinforced resin composites. *Dent Mater*. 2021;37(6):983-997.
18. Rocha MG, Maucoski C, Roulet JF, Price RB. Depth of cure of 10 resin-based composites light-activated using a laser diode, multi-peak, and single-peak light-emitting diode curing lights. *J Dent*. 2022;122:104141.
19. Kouros P, Dionysopoulos D, Deligianni A, Strakas D, Sfeikos T, Tolidis K. Evaluation of photopolymerization efficacy and temperature rise of a composite resin using a blue diode laser (445 nm). *Eur J Oral Sci*. 2020;128(6):535-541.
20. Drost T, Reimann S, Frentzen M, Meister J. Effectiveness of photopolymerization in composite resins using a novel 445-nm diode laser in comparison to LED and halogen bulb technology. *Lasers Med Sci*. 2019;34(4):729-736.
21. AMD. Monet laser curing light. The 1 second revolution. Accessed 12 October, 2021. https://www.amdlasers.com/pages/monet-laser-curing-light-intro.
22. VISTA APEX. PinkWave - light curing evolved. Accessed July 18, 2022. https://vistaapex.com/pinkwave/.
23. Ultradent. Valo X Curing Light. Accessed 23 December, 2022. https://www.ultradent.com/resources/product-instructions
24. Maucoski C, Price RB, Arrais CAG, Sullivan B. In vitro temperature changes in the pulp chamber caused by laser and quadwave LED-light curing units. *Odontology*. 2022. doi:10.1007/s10266-022-00780-y
25. Ilie N, Watts DC. Outcomes of ultra-fast (3s) photo-cure in a RAFT-modified resin-composite. *Dent Mater*. 2020;36(4):570-579.
26. Ilie N, Diegelmann J. Impact of ultra-fast (3s) light-cure on cell toxicity and viscoelastic behavior in a dental resin-based composite with RAFT-mediated polymerization. *J Mech Behav Biomed Mater*. 2021;124:104810.
27. Zarpellon DC, Runnacles P, Maucoski C, et al. In vivo pulp temperature changes during class V cavity preparation and resin composite restoration in premolars. *Oper Dent*. 2021;46:374-384.
28. Akarsu S, Aktug KS. Influence of bulk-fill composites, polimerization modes, and remaining dentin thickness on Intrapulpal temperature rise. *Biomed Res Int*. 2019;2019:1-7.
29. Savas S, Botsali MS, Kucukyilmaz E, Sari T. Evaluation of temperature changes in the pulp chamber during polymerization of light-cured pulp-capping materials by using a VALO LED light curing unit at different curing distances. *Dent Mater J*. 2014;33(6):764-769.
30. 3M. Filtek One Bulk Fill Restorative. Accessed 23 December, 2022. https://multimedia.3m.com/mws/media/1317671O/3m-filtek-one-bulk-fill-restorative-technical-product-profile.pdf
31. Harlow JE, Rueggeberg FA, Labrie D, Sullivan B, Price RB. Transmission of violet and blue light through conventional (layered) and bulk cured resin-based composites. *J Dent*. 2016;53:44-50.
32. Armellin E, Bovesecchi G, Coppa P, Pasquantonio G, Cerroni L. LED curing lights and temperature changes in different tooth sites. *Biomed Res Int*. 2016;2016:1-10.
33. Runnacles P, Arrais CA, Pochapski MT, et al. In vivo temperature rise in anesthetized human pulp during exposure to a polywave LED light curing unit. *Dent Mater*. 2015;31(5):505-513.
34. Masutani S, Setcos JC, Schnell RJ, Phillips RW. Temperature rise during polymerization of visible light-activated composite resins. *Dent Mater*. 1988;4(4):174-178.
35. Baroudi K, Silikas N, Watts DC. In vitro pulp chamber temperature rise from irradiation and exotherm of flowable composites. *Int J Paediatr Dent*. 2009;19(1):48-54.
36. Al-Qudah AA, Mitchell CA, Biagioni PA, Hussey DL. Thermographic investigation of contemporary resin-containing dental materials. *J Dent*. 2005;33(7):593-602.
37. Chiang YC, Lee BS, Wang YL, et al. Microstructural changes of enamel, dentin-enamel junction, and dentin induced by irradiating outer enamel surfaces with CO_2 laser. *Lasers Med Sci*. 2008;23(1):41-48.
38. Aguiar FH, Barros GK, Lima DA, Ambrosano GM, Lovadino JR. Effect of composite resin polymerization modes on temperature rise in human dentin of different thicknesses: an in vitro study. *Biomed Mater*. 2006;1(3):140-143.
39. Murray PE, Smith AJ, Windsor LJ, Mjor IA. Remaining dentine thickness and human pulp responses. *Int Endod J*. 2003;36(1):33-43.
40. Yazici AR, Muftu A, Kugel G, Perry RD. Comparison of temperature changes in the pulp chamber induced by various light curing units, in vitro. *Oper Dent*. 2006;31(2):261-265.
41. Jakubinek MB, O'Neill C, Felix C, Price RB, White MA. Temperature excursions at the pulp-dentin junction during the curing of light-activated dental restorations. *Dent Mater*. 2008;24(11):1468-1476.
42. Nilsen BW, Mouhat M, Haukland T, Ortengren UT, Mercer JB. Heat development in the pulp chamber during curing process of resin-based composite using multi-wave LED light curing unit. *Clin Cosmet Investig Dent*. 2020;12:271-280.
43. Vatansever F, Hamblin MR. Far infrared radiation (FIR): its biological effects and medical applications. *Photon Lasers Med*. 2012;4:255-266.
44. Dederich DN. Laser/tissue interaction: what happens to laser light when it strikes tissue? *J Am Dent Assoc*. 1993;124(2):57-61.
45. Par M, Repusic I, Skenderovic H, Milat O, Spajic J, Tarle Z. The effects of extended curing time and radiant energy on microhardness and temperature rise of conventional and bulk-fill resin composites. *Clin Oral Investig*. 2019;23(10):3777-3788.
46. Grazioli G, Cuevas-Suarez CE, Mederos M, et al. Evaluation of irradiance and radiant exposure on the polymerization and mechanical properties of a resin composite. *Braz Oral Res*. 2022;36:e082.
47. Ilie N, Schmalz G, Fujioka-Kobayashi M, Lussi A, Price RB. Correlation of the mechanical and biological response in light-cured RBCs to receiving a range of radiant exposures: effect of violet light. *J Dent*. 2021;105:103568.
48. Runnacles P, Arrais CAG, Maucoski C, Coelho U, De Goes MF, Rueggeberg FA. Comparison of in vivo and in vitro models to evaluate pulp temperature rise during exposure to a Polywave(R) LED light curing unit. *J Appl Oral Sci*. 2019;27:e20180480.
49. Kodonas K, Gogos C, Tziafas D. Effect of simulated pulpal microcirculation on intrapulpal temperature changes following application of heat on tooth surfaces. *Int Endod J*. 2009;42(3):247-252.
50. Kodonas K, Gogos C, Tziafa C. Effect of simulated pulpal microcirculation on intrachamber temperature changes following application of various curing units on tooth surface. *J Dent*. 2009;37(6):485-490.

51. Gross DJ, Davila-Sanchez A, Runnacles P, et al. In vivo temperature rise and acute inflammatory response in anesthetized human pulp tissue of premolars having class V preparations after exposure to Polywave(R) LED light curing units. *Dent Mater*. 2020;36(9):1201-1213.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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