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Effect of Simulated Pulpal Microcirculation on Temperature When Light Curing Bulk Fill Composites

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Clinical Relevance

Ex vivo studies should simulate pulpal microcirculation when attempting to measure the temperature rise that occurs during light curing. The greatest potential for an intrapulpal temperature rise occurs when the adhesive is light cured.

SUMMARY

Objectives: To evaluate the effect of light curing bulk fill resin composite restorations on the increase in the temperature of the pulp chamber both with and without a simulated pulpal fluid flow.

Methods and Materials: Forty extracted human molars received a flat occlusal cavity, leaving approximately 2 mm of dentin over the pulp. The teeth were restored using a self-etch adhesive system (Clearfil SE Bond, Kuraray) and two different bulk fill resin composites: a flowable (SDR, Dentsply) and a regular paste (AURA, SDI) bulk fill. The adhesive was light cured for 20 seconds, SDR was light cured for 20 seconds, and AURA was light cured for 40 seconds using the Bluephase G2 (Ivoclar Vivadent) or the VALO Cordless (Ultradent) in the

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standard output power mode. The degree of conversion (DC) at the top and bottom of the bulk fill resin composite was assessed using Fourier-Transform Infra Red spectroscopy. The temperature in the pulp chamber when light curing the adhesive system and resin composite was measured using a J-type thermocouple both with and without the presence of a simulated microcirculation of 1.0-1.4 mL/min. Data were analyzed using Student *t*-tests and two-way and three-way analyses of variance (α=0.05 significance level).

Results: The irradiance delivered by the light-curing units (LCUs) was greatest close to the top sensor of the MARC resin calibrator (BlueLight Analytics) and lowest after passing through the 4.0 mm of resin composite plus 2.0 mm of dentin. In general, the Bluephase G2 delivered a higher irradiance than did the VALO Cordless. The resin composite, LCU, and region all influenced the degree of cure. The simulated pulpal microcirculation significantly reduced the temperature increase. The greatest temperature rise occurred when the adhesive system was light cured. The Bluephase G2 produced a rise of 6°C, and the VALO Cordless produced a lower temperature change (4°C) when light curing the adhesive system for 20 seconds without pulpal microcirculation. Light curing SDR produced the greatest exothermic reaction.

Conclusions: Using simulated pulpal microcirculation resulted in lower temperature increases. The flowable composite (SDR) allowed more light transmission and had a higher degree of conversion than did the regular paste (AURA). The greatest temperature rise occurred when light curing the adhesive system alone.

INTRODUCTION

Resin composites are widely used in restorative dentistry, and they can provide good clinical longevity.[1] The light output from curing lights is greater now than in the past, and this may be the reason why the patient experiences some postoperative pain. This may be related to the thermal, osmotic, and mechanical stimuli that cause rapid movement of fluid in dentinal tubules.[2,3] Several other factors can also affect pulp health, such as the presence of caries, chemical trauma, or thermal changes.[4] Excessive heating of the pulp is a concern in dental treatment because it can cause an inflammatory reaction, histopathological changes, vascular damage, and even cell death.[5]

Heat can be generated or transferred to the dentin-pulp complex during tooth preparation, when light curing, when polishing the restoration, or during light-activated bleaching.[6,7] The resulting rise in pulpal temperature is dependent on the duration of the light exposure[8]; the radiant power and energy from the light-curing unit (LCU); the amount of dentin thickness remaining[9]; the LCU[10]; the resin composite type, thickness, and shade; or the exothermic reaction as the resin polymerizes.[11-13] LCUs that deliver a high irradiance may produce a larger temperature rise,[10] and it is possible that a damaging temperature rise may occur during resin photopolymerization.[4,14]

The amount of heat generated when light curing resin-based composites depends on the curing light, type of composite, and the substrate used in the experiment.[15] Dark shades of resin composites tend to produce a lower initial temperature rise, but the temperature remains elevated for longer because the light penetration is reduced and polymerization occurs more slowly in the darker shades of composites.[11] Some bulk fill resin composites have been reported to cause greater temperature increases than when the composites are placed and light cured in increments.[16] Flowable composites tend to produce a greater temperature increase due to their greater resin content and lower filler load.[17] However, more studies are required using other bulk fill resin composites, especially those that have different viscosities.

When conducting laboratory tests, the *in vivo* conditions should be simulated as closely as possible. The movement of fluid in dentin tubules, or changes in pulp blood flow due to stimulation of the nervous system within the pulp, are both affected by different thermal stimuli *in vivo*.[18] The response can be increased by operative procedures,[6] or it can be less after delivery of a local anesthetic.[19] The intrapulpal blood circulation has been estimated to be 40 mL/min per 100 g of tissue,[20,21] and this fluid flow may be sufficient to dissipate some or all of the heat from external thermal stimuli to the dentin-pulpal complex.[18] Since it is considered that the absence of water and lack of fluid flow reduce the conduction of heat and the clinical relevance of a study,[7] some *in vitro* studies have used teeth positioned in a vessel containing water at 37°C, and have made some attempt to simulate the pulpal pressure.[8,22] Relatively few studies have measured the temperature rise in combination with a simulated pulpal micro-

Table 1: *Characteristics of the Dental Curing Lights Tested. Mean Values (Standard Deviations)*

LCU	VALO Cordless	Bluephase G2
Irradiance, mW/cm^2	1297.9 (3.3)	1393.8 (4.5)
Wavelength, nm	395-480	385-515
Manufacturer	Ultradent, South Jordan, UT, USA	Ivoclar Vivadent, Schaan, Liechtenstein

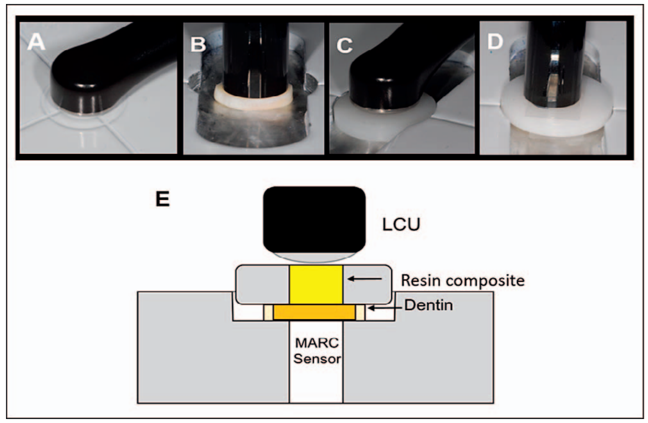

Figure 1. *Illustration of how the irradiance (mW/cm^2) and emission spectrum (mW/cm^2/nm) of LCU were measured: (A) VALO Cordless over the MARC-RC top sensor; (B) Bluephase G2 over 2.0-mm thickness of dentin on MARC-RC bottom sensor; (C) VALO Cordless over the 4.0 mm of bulk fill resin composite; (D) Bluephase G2 over the 4.0 mm of bulk fill resin composite plus 2.0 mm of dentin on MARC-RC bottom sensor; (E) Schematic of the specimen and LCU position in the MARC-RC system.*

circulation (combined simulated pulpal fluid flow and pressure).[6,7]

The aim of this study was to evaluate the effect of simulated pulpal microcirculation using a novel device developed for this study to simulate both pulp fluid flow and pressure. The effect of the LCU on the temperature rise in the pulp chamber caused when light curing the adhesive system followed by light curing two different bulk fill composites in deep, flat cavities was examined. The null hypotheses were that 1) the simulated pulp fluid flow and light-curing unit would have no effect on the intrapulpal temperature rise, and 2) the different irradiances and radiant exposures from the two curing lights would have no effect on the rise in the intrapulpal temperature and on the degree of conversion of the bulk fill resin composites.

METHODS AND MATERIALS

Study Design

Two broad-spectrum multipeak LCUs, Bluephase G2 (Ivoclar Vivadent, Schaan, Liechtenstein) and VALO Cordless (Ultradent, South Jordan, UT, USA), and a flowable bulk fill composite, SDR, SureFil SDR flow (Dentsply, Konstanz, Germany) and a bulk fill paste composite, AURA, Aura Bulk Fill (SDI, Bayswater, Perth, Australia), were used. The characteristics of the LCUs are described in Table 1, and the composites and their composition are listed in Table 2. The irradiance, emission spectrum, and radiant exposure from the LCUs were characterized using a MARC resin calibrator (BlueLight Analytics Inc, Halifax, NS, Canada). The degrees of conversion (DCs) at the top and bottom of the resin composite samples were assessed using Fourier-Transform mid–Infrared Spectroscopy (FT-midIR; Vertex 70, Bruker Optik GmbH, Ettlingen, Germany). Forty extracted human maxillary molars (Ethics Committee in Human Research of Federal University of Uberlandia approval No. 1.451.872) received standardized 5 × 5-mm occlusal cavity preparations that were 4 mm deep, leaving 2.0 mm of dentin over the pulp. Following the manufacturers' instructions, a self-etching adhesive system (Clearfil SE Bond, Kuraray, Tokyo, Japan) was applied to the dentin. The pulp temperature was measured both during light curing of the adhesive system and of the resin composite using J-type thermocouple (Ecil Produtos, SP, Brazil) inserted into the pulp chamber. The temperature was measured both with and without a simulated pulpal microcirculation of 1.0-1.4 mL/min through the pulp chamber and the temperature was recorded at the rate of 1Hz. The thermocouple was connected to a data acquisition device (ADS2000IP; Lynx Technology, São Paulo, SP, Brazil) to measure the exothermic reaction.

Irradiance, Emission Spectrum, and Radiant Exposure

The irradiance (mW/cm^2), emission spectrum (mW/cm^2/nm), and radiant exposure (J/cm^2) delivered by each LCU operating in the standard mode to the resin composites were measured using a MARC resin calibrator (RC). The measurements were recorded five times under different conditions: control–top; through 2.0 mm of dentin; through 4.0 mm of each resin composite; and through 4.0 mm of each resin composite over 2.0 mm of dentin.

Control–Top—The irradiance at the tip of each LCU was determined by placing the tip directly over and at a distance of 0 mm from the MARC-RC top sensor (Figure 1A). The Bluephase G2 delivered 27.7 J/cm^2 and the VALO Cordless delivered 25.7 J/cm^2, when used for 20 seconds. When used for 40 seconds,

Table 2: *Dental Composites Tested in the Study (Information Provided by the Manufacturers)*

Composite	Wt%	Vol%	Filler Type	Matrix	Manufacturer Resins
AURA	81	65	Silica, barium alumino-borosilicate glass	Bis-EMA, UDMA, TEGDMA	SDI (Bayswater, Perth, Australia)
SDR	68	44	Barium and strontium alumino-fluoro-silicate glasses	Modified UDMA, dimethacrylate and difunctional diluents	Dentsply (Konstanz, BW, Germany)

Abbreviations: Bis-EMA, bisphenol-A hexaethoxylated dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

the Bluephase G2 delivered 49.7 J/cm^2 and the VALO Cordless 49.4 J/cm^2.

Through 2.0 mm of Dentin—To estimate the irradiance, emission spectrum, and radiant exposure through dentin (Figure 1B), one human upper molar was sectioned using a low-speed diamond saw (Isomet, Buehler, Lake Bluff, IL, USA) using copious water cooling to obtain one slice of 2.0-mm-thick pulpal dentin. This 2.0-mm-thick dentin sample was placed directly on the surface of the MARC sensor, and the LCU was turned on. Before each measurement (n=5), the dentin slice was immersed in water for one minute so that it was hydrated.

Through 4.0 mm of Bulk Fill Resin Composite—To estimate the irradiance, emission spectrum, and radiant exposure transmitted through each bulk fill resin composite during photocuring (Figure 1C), a plastic ring mold (Delrin Ring, DuPont, Mississauga, ON, Canada) with an internal aperture of 6-mm diameter and 4 mm height was filled with each resin composite. A Mylar strip (DuPont Teijin Films, Hopewell, VA, USA) was placed over the MARC bottom sensor, the ring matrix was centered over the sensor, and the LCUs were turned on for 20 seconds for SDR and for 40 seconds for AURA (n=5).

Through 4.0 mm of Bulk Fill Resin Composite and 2.0 mm of Dentin—To estimate the irradiance, emission spectrum, and radiant exposure transmitted through the resin composite and dentin (Figure 1D,E), the slice of 2.0-mm dentin sample was placed directly on the surface of the MARC bottom sensor, a Mylar strip was placed over the dentin, and the Delrin ring filled with each uncured resin composite was placed over the dentin slice. The LCU was then turned on (according to the manufacturers' instructions) for 20 seconds for SDR and for 40 seconds for AURA (n=5).

The same trained operator conducted all of the light exposures. The tip of the LCU was fixed as close as possible to the surface of the resin with a rigid clamp. The MARC software displayed the maximum irradiance (mW/cm^2), radiant exposure (J/cm^2), and the emission spectrum (mW/cm^2/nm) received by the sensor.

DC of Resin Composites

The DCs at the top and bottom of the bulk fill resin composite samples (n=5) were assessed after 24 hours. The samples were prepared in a dark room with yellow light so that the room light did not impact the resin polymerization. After light curing with the LCU, the samples were then stored dry at 37°C, protected from light. The DCs were assessed using FT-midIR (Vertex 70, Bruker Optik GmbH) with attenuated total reflectance (ATR crystal) sampling, mid-infrared (MIR) and deuterated triglycine sulfate (DTGS) detector elements (Bruker Optik GmbH). The spectra were obtained between internal standard aromatic C=C bonds (1608 cm^{-1}) and aliphatic C=C bond (1638 cm^{-1}), at a resolution of 4 cm^{-1}, and 32 scans were averaged. All analyses were performed under controlled temperature (25°C$\pm$1°C) and humidity (60%$\pm$5%) conditions. DC was calculated from the equivalent aliphatic (1638 cm^{-1}) and aromatic (1608 cm^{-1}) ratios of cured (C) and uncured (U) resin composite specimens. The formula used to calculate the degree of conversion was $DC\ (\%) = (1 - C/U) \times 100$.

Tooth Preparation and Dentin Thickness Measurement

The temperature inside the pulp was measured using custom-made microcirculation equipment (Figure 2A) that was developed by the authors in partnership with ODEME (Luzerna, SC, Brazil). This equipment is currently under patent review (Protocol INPI No. BR 10 2016 016624 1). Forty extracted, intact, caries-free human maxillary third molars of young patients (18-20-year age range) were used in this study (Ethics Committee in Human Research of Federal University of Uberlandia approval No. 1.451.872). The inclusion criteria required the molars to have wide pulp chambers, two separate roots, and open apices. The apices of the roots were sectioned 5.0 mm from the furcation to expose the root canals. After cleaning the root canals, 1.2-mm-diameter metal tubes (40 × 1.2 18G1 irrigation needles; Embramac, Campinas, SP, Brazil) were inserted 2 mm into the root canal

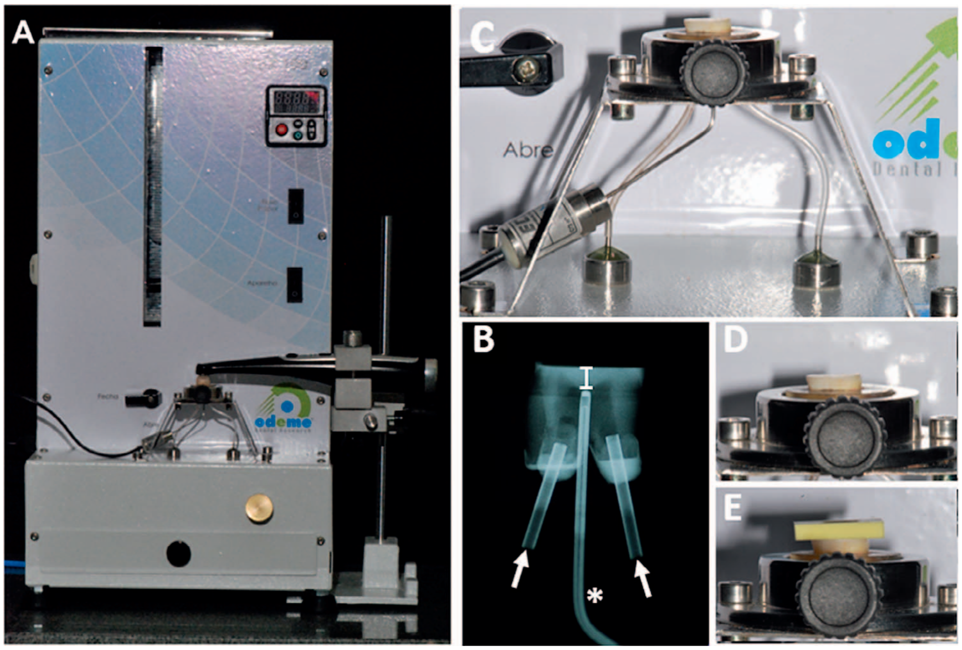

Figure 2. *Temperature measurement: (A) Equipment to simulate pulpal microcirculation, temperature measurement, and the LCU support; (B) Tooth, plastic tubes carrying the water connected to the sample, and thermocouple inserted into the pulp chamber; (C) X-ray of tooth sample with two metallic tubes and the thermocouple in contact with the top of dentin pulp floor where it is ~2 mm thick (region above the thermocouple); the arrows indicate the needles and the asterisk indicates the thermocouple; (D) Light curing the adhesive system; (E) Light curing the bulk fill using a silicon matrix to position the light in the same position each time.*

orifices, one in the palatal root and the other in the buccal root, while keeping 5 mm of the metal tubes exposed outside the tooth. The tubes were fixed using resin composite (Z250, 3M-ESPE, St Paul, MN, USA). The third root was sealed with the same resin composite. The teeth to be tested without any simulated pulpal microcirculation had their roots sealed with resin composite. The roots of the teeth were embedded in 10 mm of polystyrene resin (Cristal, Piracicaba, SP, Brazil), to a level just below the cemento-enamel junction. The pulp chamber was accessed through the furcation using a diamond bur (No. 1016 HL KG Sorensen, Barueri, SP, Brazil) in a high-speed handpiece with copious air-water spray to prevent damage to the pulp-dentin at the top of the pulp chamber. A radiograph (Kodak Dental Systems, Carestream Health, Rochester, NY, USA) was taken for each tooth to confirm the crown dimension and pulp chamber location so that the flat cavities (5 × 5 × 4 mm deep) were made to be approximately 2 mm above the pulp chamber. After preparation, another radiograph was taken to confirm the thickness of dentin remaining (in millimeters) and the position of the thermocouple. Figure 2B illustrates how the pulp-dentin remaining thickness was measured using ImageJ software (National Institutes of Health, Bethesda, MD, USA).

Temperature Rise Measurement

A J-type thermocouple with a 10-Hz response time (Ecil Produtos e Sistemas para Medição e Controle Ltda, Piedade, SP, Brazil) was inserted into the pulp chamber through the access hole in the furcation so that it contacted the pulp dentin floor at the top of the pulp chamber. This thermocouple was used to measure the temperature change produced inside the pulp chamber when light curing the self-etching adhesive system alone and then when light curing the bulk fill resin composites. This J-type thermocouple can measure temperature variations ranging from 0°C to 480°C at a rate of 10 Hz. The thermocouple was also connected to the simulated pulpal microcirculation equipment. The temperatures recorded were transferred to a computer using a dedicated software interface. The real-time data were recorded at 1 Hz and expressed both graphically and as an exportable data file.

The custom-designed pulpal microcirculation device has a peristaltic pump and reservoir with both an adjustable thermal and pressure control. The hydrostatic pulp pressure was adjusted to 20 cm H_2O.[22,23] The pulpal temperature was maintained at 37°C,[6,7] and distilled water was pumped through the pulp at a rate of 1.0-1.4 mL/min.[6,7] Two polyethylene tubes, one for water inflow and one for water outflow, were connected to the metal tubes in the tooth roots (Figure 2C).

The teeth were divided into eight groups (n=5) that were defined by three study factors: simulated pulpal microcirculation, no pulpal microcirculation; Bluephase G2 or VALO Cordless LCUs; and the bulk fill resin composites, SDR or AURA. The self-etching adhesive system (Clearfil SE Bond, Kuraray) was used according to the manufacturer's instructions. The primer was actively applied over the flat tooth surface for 10 seconds and dried using a gentle air flow; the adhesive was then applied, the excess was removed with a microbrush (KG Sorensen), and light cured for 20 seconds with the tip positioned close to, but not touching, the dentin (Figure 2D). The restoration was made over the flat dentin surface using a standardized polyvinyl siloxane impression matrix (Express XT, 3M-ESPE) that was 5 × 5 mm wide and 4 mm deep (Figure 2E). The matrix was centered over the flat tooth surface and carefully filled in bulk, avoiding the incorporation of any air bubbles. The resin composite was light cured for 20 seconds (SDR) and for 40 seconds (AURA). The temperature was recorded during the restorative process, and the peak maximum temperature was calculated at two timepoints: when light curing the adhesive system and when light curing the resin composite.

Exotherm of Materials

A second J-type thermocouple (5TC-TT-J-40-36; Alutal Siebeck Sensors, São Paulo, SP, Brazil) was used to measure the exothermic reaction of the light curing of materials used. This thermocouple was connected to the data acquisition device (AD-S2000IP; Lynx Technology, São Paulo, SP, Brazil). The data were transferred to a computer using specific acquisition signal transformation by data analysis software (AqDados 7.02 and AqAnalisys; Lynx). To measure the exothermic reaction of bulk fill resin composites, it was placed in one 4.0-mm increment (n=10). To measure the exothermic reaction of the adhesive, it was placed in a thin layer on the thermocouple tip (n=10). The LCUs were then positioned at 1.0 mm above the material, which were then light cured according to manufacturers' instructions: SDR and the adhesive both for 20 seconds, whereas the AURA was exposed for 40 seconds. The samples were prepared in a dark room with yellow light. The temperature was recorded before start of light curing. After the first light exposure, the samples were exposed three more times, after two, four, and six minutes. The mean of these three re-irradiations was calculated and represented that the temperature rise during the final postcure was due to the curing light and had no resin exotherm. To determine the contribution of the exothermic reaction to the temperature rise, the mean of the postcure temperature profile was subtracted from the temperature profile obtained during the first light exposure.[15,24]

Statistical Analysis

The dentin thickness (mm), maximum irradiance (mW/cm^2), DC of resin composite (%), temperature change (°C), and exothermic reaction (°C) data were tested for a normal distribution (Shapiro-Wilk, $p>0.05$) and equality of variances (Levene test), followed by parametric statistical tests. The Student *t*-test was used to compare the dentin thickness (mm). Two-way analysis of variance (ANOVA) was used to compare the effect of the resin composite, LCU, and their interaction for irradiance and radiant exposure data. Three-way ANOVA was used to compare the effect of the resin composite, LCU, and sample area on the DC data. Two-way ANOVA was used to compare the effect of the LCU and simulated pulpal microcirculation on the temperature rise when light curing the adhesive system. Three-way ANOVA was used to compare effect of the resin composite, LCU, and the effect of simulated pulpal microcirculation on the temperature rise data when light curing the resin composite. A paired Student *t*-test was used to compare the temperature rise when light activating the adhesive system and the resin composite, for all experimental conditions. Two-way ANOVA was used to compare the effect of material, LCU, and their interaction for exothermic reaction. All tests used an $\alpha = 0.05$ significance level, and all analyses were carried out using Sigma Plot version 13.1 (Systat Software Inc, San Jose, CA, USA). The light emission spectra were analyzed qualitatively.

RESULTS

Dentin Remaining Thickness (mm)

Based on the measurements taken from the radiographs, the thickness of the pulp floor dentin of the teeth randomly allocated to the AURA group was 1.89 ± 0.42 mm. This was statistically similar ($p=0.596$) to the measurement for the teeth allocated to the SDR group (1.99±0.43 mm).

Irradiance and Emission Spectrum Emitted by LCUs

The maximum irradiance (mW/cm^2), emission spectrum (mW/cm^2/nm), and radiant exposure (J/cm^2) emitted by the two LCUs at different positions simulating the experimental conditions are reported in Table 3 and Figure 3, respectively.

Two-way ANOVA showed that a significant interaction effect was observed between light-curing units and how the irradiance delivered to the resin composites by LCUs was measured ($p<0.001$). As

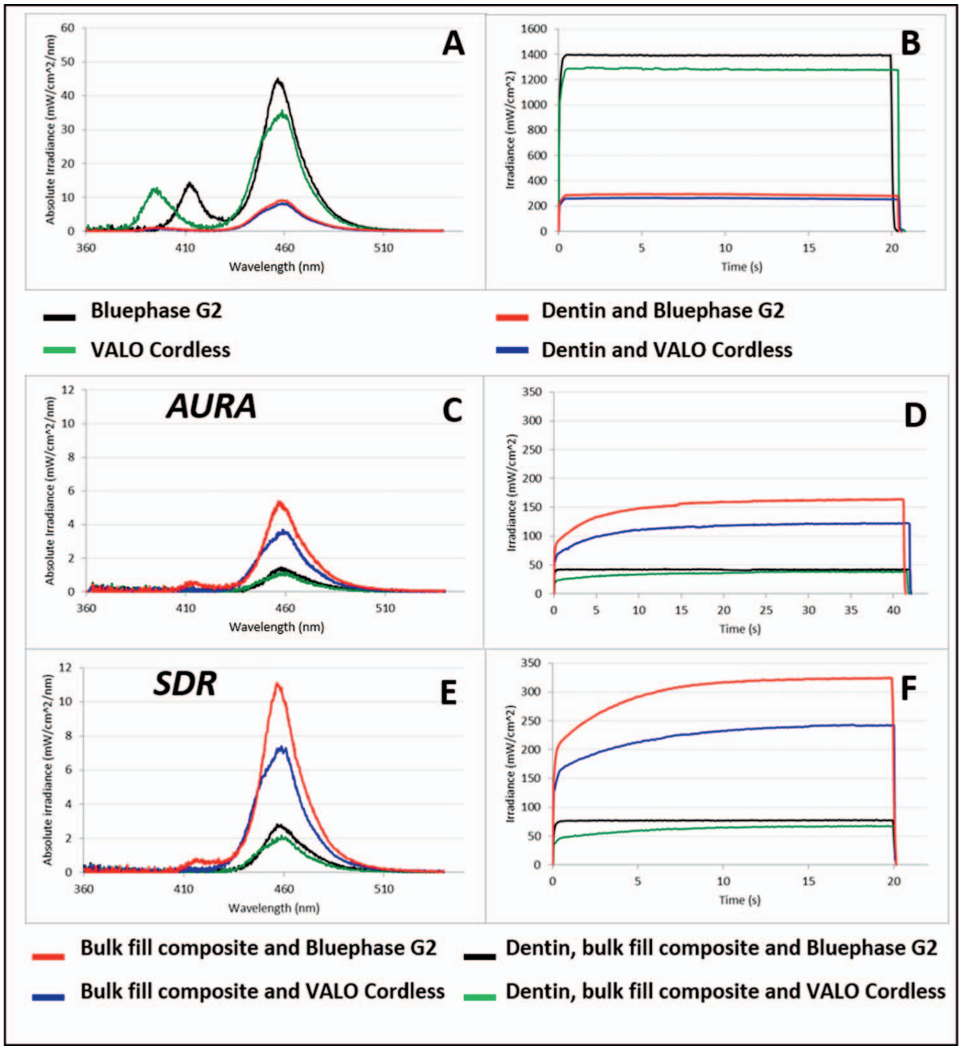

Figure 3. *Emission spectrum (mW/cm²/nm) and irradiance (mW/cm²) from the LCUs: (A) Emission spectrum of LCUs over the top sensor and through dentin on MARC bottom sensor; (B) Irradiance of LCUs over the top sensor and through dentin on bottom sensor; (C) Emission spectrum through AURA and 2.0-mm-thick dentin; (D) Irradiance through AURA and 2.0-mm-thick dentin; (E) Emission spectrum through SDR and 2.0-mm-thick dentin; (F) Irradiance through SDR and 2.0-mm-thick dentin. Note the irradiance scales are different in A compared to C and E. The scales are also different in B compared to D and F.*

expected, the irradiance emitted by LCUs was significantly greater when closer to the top sensor, and this effect was reduced by as much as 97.2% when measured through the 4.0 mm of AURA resin composite over 2.0 mm of dentin. The Bluephase G2 delivered a higher irradiance than did the VALO Cordless when measured at the top ($p<0.001$). However, no significant difference was found between both LCUs when measured through 2.0 mm of dentin plus 4.0 mm of AURA ($p=0.794$) or through 2.0 mm of dentin plus 4.0 mm of SDR ($p=0.480$).

DC (%) of Resin Composites

The means and standard deviations of the DC values for SDR and AURA at the top and bottom when light cured using Bluephase and VALO Cordless lights are shown in Table 4. Three-way ANOVA showed that only resin composite ($p<0.001$), LCU ($p<0.001$), and the region ($p<0.001$) significantly influenced the DC. Even though it was only exposed for 20 seconds, SDR had significantly higher DC than did AURA, regardless of the LCU used and the region measured. Despite delivering a lower irradiance, using the VALO Cordless produced a higher DC than did the Bluephase G2, regardless of the resin composite or the region measured. The top of the specimens achieved a higher DC than did the bottom, regardless of the resin composites or the LCU used.

Temperature Rise Measurement

The means and standard deviations of the maximum temperature change at the roof of the pulp chamber measured when light curing the adhesive system are shown in Figure 4. Two-way ANOVA showed that there was a significant interaction effect when the microcirculation through the pulp was simulated and on the LCUs that were used when light curing the adhesive system ($p<0.001$). When light curing

Table 3: *Irradiance (mW/cm²) Delivered by the Dental Curing Lights Under Different Conditions and Percent of Light Attenuation in Relation to the Control. (Control–Top: the Tip Irradiance of the Light-curing Units [LCUs] Was Determined by Placing the Light Tip Directly Over and at a Distance of 0 mm From the MARC-RC Sensor)[a] (ext.)*

LCUs	Control–Top	Through 2.0 mm of Dentin	Through 4.0 mm of AURA
VALO Cordless	1297.9 (3.3) Ab	237.6 (3.0) Bb 81.7%	124.2 (3.2) Cb 90.4%
Bluephase G2	1393.8 (4.5) Aa	290.6 (9.8) Ba 79.2%	166.0 (7.5) Ca 88.1%

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the condition of measurement, and lowercase letters are used for comparing the LCU (p<0.05).*

the adhesive system, the lack of any pulpal microcirculation resulted in a greater temperature change than was noted when pulpal microcirculation was simulated, regardless of the light-curing unit used ($p<0.001$). The VALO Cordless (dose delivered: 25.7 J/cm²) produced a smaller temperature increase (4°C) compared to the Bluephase G2 (dose delivered: 27.7 J/cm²), which produced a 6°C increase when light curing the adhesive system when no pulpal microcirculation was present. (Figure 4; $p<0.001$).

The means and standard deviations of the maximum temperature change at the roof of the pulp chamber measured during light curing of the bulk fill resin composites are shown in Table 5. The three-way ANOVA only revealed a significant effect when the pulpal microcirculation was simulated ($p<0.001$). The temperature change was significantly greater without a simulated pulpal microcirculation than when the pulpal microcirculation was simulated, regardless of choice of light-curing unit and bulk fill resin composites. No significant difference was observed between VALO Cordless and Bluephase G2 ($p=0.974$) and also between AURA and SDR ($p=0.340$), between interaction of two factors—LCUs and resin composite ($p=0.564$); LCUs and simulated pulpal microcirculation ($p=0.438$), resin composite, and simulated pulpal microcirculation ($p=0.284$); and also for interaction among three study factors—simulated pulpal microcirculation, LCUs, and resin composite ($p=0.857$).

The temperature changes produced by light activation of the adhesive system and resin composite with and without the simulated pulpal microcirculation are shown in Figure 4. The paired Student *t*-test showed that the temperature changes were significantly higher when light curing the adhesive system compared to when the resin composite was light cured (temperature difference of 3°C) for all combinations where the pulpal microcirculation was not simulated. However, no difference was found for any combination where the pulpal microcirculation was simulated.

Exothermic Reaction Measurement

The means and standard deviations of exothermic reaction for the adhesive system, SDR and AURA, when light cured using Bluephase G2 and VALO Cordless lights are shown in Table 6. Two-way ANOVA showed significant difference between materials ($p<0.001$). The exotherm was significantly higher for the 4.0-mm increment of SDR (7.7°C, Bluephase G2; 8°C, VALO Cordless) than for the 4.0-mm increment of AURA (4.7°C, Bluephase G2; 4.5°C, VALO Cordless). No significant difference was observed between VALO Cordless and Bluephase G2 ($p=0.528$) and also between the interaction of two factors—LCUs and material ($p=0.753$).

DISCUSSION

The use of simulated pulpal microcirculation, intrapulpal pressure, and the choice of LCU influenced the temperature rise in the pulp chamber when light curing the two resin-based composites used in this study. Furthermore, the irradiance from the two LCUs was significantly different through the dentin,

Table 4: *Mean (Standard Deviation) Degree of Conversion (%) of the Resin Composites at the Top and Bottom After Light Curing and the Percent of Light Attenuation[a]*

Resin Composites	Bluephase G2			VALO Cordless		
	Top	Bottom	Difference: Bottom to Top DC	Top	Bottom	Difference: Bottom to Top DC
AURA	65.6 (5.4) Bb	61.9 (4.5) Bb	5.6%	76.4 (3.2) Aa	66.6 (6.3) Bb	12.8%
SDR	76.4 (3.2) Aa	64.6 (2.7) Aa	15.5%	79.7 (3.3) Aa	75.6 (4.7) Aa	5.2%

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the composite resins, and lowercase letters are used for comparing light curing units (p<0.05).*

Table 3: *Extended.*

LCUs	Through 4.0 mm of SDR	Through SDR 4.0 mm + Dentin 2.0 mm	Through AURA 4.0 mm + Dentin 2.0 mm
VALO Cordless	237.2 (13.5) Da 81.7%	67.2 (9.6) Ea 94.8%	37.0 (1.6) Fa 97.2%
Bluephase G2	324.2 (21.7) Db 76.7%	71.3 (6.1) Ea 94.9%	38.5 (4.2) Fa 97.2%

and the bulk fill resin composites. Therefore, the null hypotheses were rejected.

To achieve the ideal mechanical properties the resin composites must receive sufficient energy at the appropriate wavelengths.[25] Although there was a difference between the two resin composites, both produced a high DC, confirming that sufficient light was able to reach to the bottom of 4 mm of the composite when the exposure times recommended by the manufacturers were used. For 20 s, the dose delivered at the top of the SDR samples from Bluephase G2 was 27.7 J/cm^2, and the dose was 25.7 J/cm^2 from VALO Cordless; at the bottom, 5.5 J/cm^2 and 3.9 J/cm^2 were received from Bluephase G2 and VALO Cordless, respectively. On the other

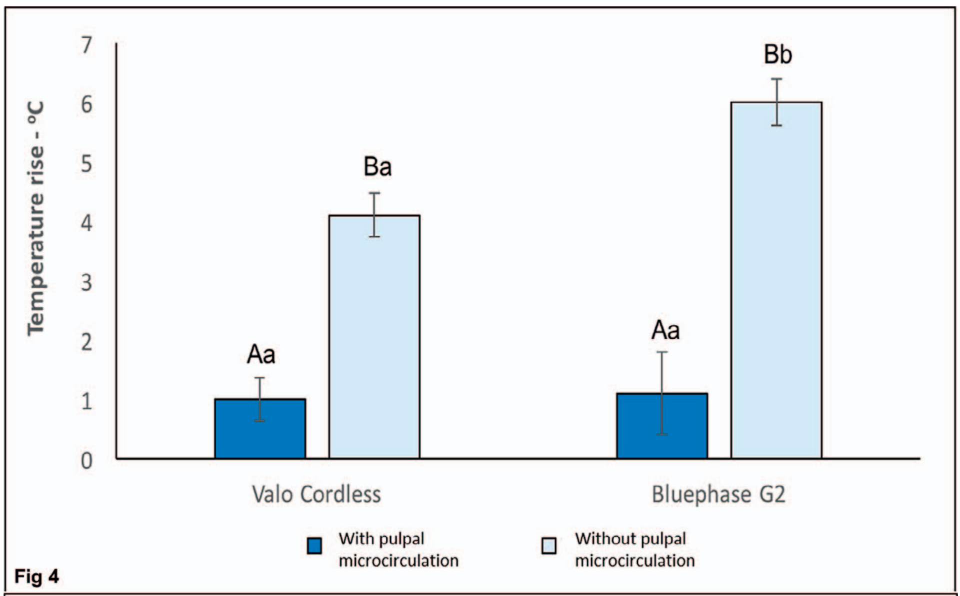

Figure 4. *Means and standard deviations of maximum temperature rise (°C) when light curing the adhesive system with and without microcirculation through the pulp (n=10). Different letters indicate a significant difference: uppercase letters used for comparing the simulated pulpal microcirculation and lowercase letters for comparing the results obtained using the two LCUs ($p<0.05$).*

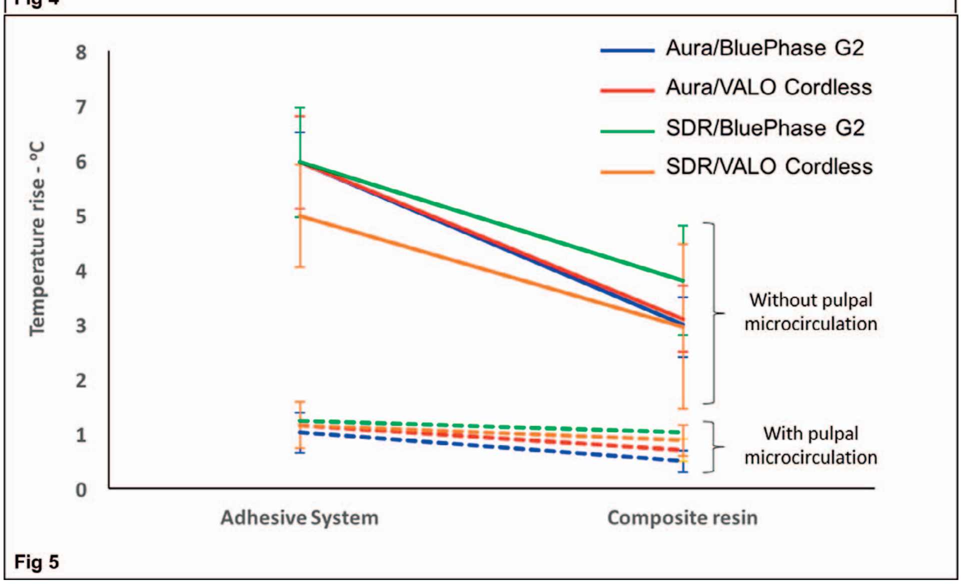

Figure 5. *Effect of pulpal microcirculation on the maximum temperature rise (means and standard deviations in °C) when light curing the adhesive system and the resin composite (n=5).*

Table 5: *Mean (Standard Deviation) Maximum Temperature Rise (°C) for Resin Composites When Light Cured With and Without Pulpal Microcirculation (n=5)[a]*

Composites	Bluephase G2		VALO Cordless	
	With Pulpal Microcirculation	Without Pulpal Microcirculation	With Pulpal Microcirculation	Without Pulpal Microcirculation
AURA	0.6 (0.2) Aa	3.0 (0.7) Ab	0.7 (0.2) Aa	3.1 (0.6) Ab
SDR	1.0 (0.4) Aa	3.1 (0.7) Ab	0.9 (0.3) Aa	2.9 (0.8) Ab

[a] *Different letters indicate a significant difference: uppercase letters used for comparing the resin composites and lowercase letters are used for comparing the simulated pulpal microcirculation ($p<0.05$).*

hand, for 40 s, the dose delivered at the top of AURA samples was 49.7 J/cm^2 from the Bluephase G2 and 49.4 J/cm^2 from the VALO Cordless, while at the bottom, only 5.3 J/cm^2 and 5.2 J/cm^2, were received for Bluephase G2 and VALO Cordless, respectively. Therefore, despite using twice the exposure time and delivering more energy, less energy reached the bottom of the AURA samples because there was greater light transmission through SDR.[26] This may explain why the SDR reached a higher DC at the bottom than did AURA, regardless of which LCU was used. Although Bluephase G2 delivered a higher irradiance and more energy than the VALO, using the VALO Cordless resulted in higher DC at the bottom of the samples. This may be because the VALO Cordless delivers a broader spectrum of light with three wavelength peaks (blue, mid-blue, and violet), while the Bluephase G2 had two peaks (violet and blue).[27] Although there was a difference between the two resin composites, both produced a high DC, confirming that sufficient light was able to reach the deep area close to the pulp dentin floor when the exposure times recommended by the manufacturers were used.

The influence of thermal stimulus on pulp temperature depends on the cavity depth and the remaining dentin thickness.[9] Enamel and dentin have a low thermal conductivity[28] and diffusivity, thus helping to protect the pulp from noxious thermal stimuli.[29] When preparing a cavity, the thickness of the remaining dentin is reduced, and the dentin tubule surface area is increased.[28] This likely explains why a larger temperature rise was observed when light curing the adhesive system and why the potential to damage the pulp is greater. Additionally, the resin composite can partially block and consume part of the emitted energy delivered by the LCU,[30] explaining the smaller temperature rise when the resin composite is light cured compared to when light curing the adhesive alone. Of note, Figure 3 shows that most of the lower wavelengths of violet light do not reach the bottom of 2 mm of dentin or 4 mm of composite.

The photons of light emitted from LCUs contain energy, and this energy can be a concern to the vitality of the pulpal tissues.[31] The heat generated depends on the irradiance delivered, the wavelength and frequency of each photon, the amount of resin composite,[25] the thickness, and the thermal conductivity of dentin.[32] Thus, it is relevant to measure the irradiance and emission spectrum delivered to the specimens and to estimate how much light reaches the pulp chamber through different materials and the remaining dentin. In this study, the emission spectrum from the LCU was recorded using a laboratory-grade spectrometer-based system. This showed that although the LCUs in this study delivered slightly different spectral emissions,[27] this small difference was unlikely to cause a difference in the temperature rise when the bulk fill composite was light cured. Flowable resin composite has a greater resin content compared to paste-like composites, and this results in a greater temperature rise from the exothermic reaction.[17,33] However, in this study no difference was observed in the temperature rise inside the pulp for both resin composites. However, there was a difference in the exothermic

Table 6: *Mean (Standard Deviation) Exothermic Reaction (°C) of the Composites When Photocured by the Light Curing Lights (LCUs)[a]*

LCUs	AURA	Clearfil	SDR
Bluephase G2	4.7 (1.3) Aa	4.7 (1.4) Aa	7.7 (0.8) Ba
VALO Cordless	4.5 (0.7) Aa	5.2 (2.1) Aa	8.0 (0.5) Ba

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the material, and lowercase letters are used for comparing the LCU ($p<0.05$).*

temperature increase produced by the two resin composites: SDR produced more heat than did AURA (temperature difference of 3°C from the Bluephase G2 and 3.5°C from the VALO Cordless). Another important aspect is that the SDR (20 seconds) received only half of the energy (27.7 J/cm^2 from the Bluephase G2 and 25.7 J/cm^2 from the VALO Cordless) compared to AURA (40 seconds) (49.7 J/cm^2 from the Bluephase G2 and 49.4 J/cm^2 from the VALO Cordless). This factor may explain the higher temperature rise for AURA than for SDR when no simulated pulpal microcirculation was used.

The temperature increase depends on many factors, such as the type of stimulus, the thickness of the dental tissues, the pulpal microcirculation,[7] and the substrate used in the experiment.[15] The lower temperature rise observed when pulpal microcirculation was simulated is most likely due to the simulated blood flow that removed some of the heat generated by the LCU.[7,31] A lack of microcirculation may overestimate values in studies that assess changes in intrapulpal temperature.[34] The blood flow in the pulp of healthy teeth has been reported to be 40 mL/min per 100 g of tissue.[20,21] To better simulate body temperature, the pulp chamber of the teeth tested is usually kept at a temperature of 37°C.[6,7] However, in a recent study it was discovered that *in vivo* the coronal human pulp is closer to 35°C.[35] In other laboratory studies, the pulp flow inside the pulp chamber was achieved by flowing distilled water at 37°C through a needle at a flow rate of 1 mL/min.[6,7] Using the equipment described in this study, it is possible to adjust both the temperature and pressure, thereby simulating different clinical conditions: for example, in simulating the increased blood flow when the dentin-pulp complex is stimulated by operative procedures,[6] or simulating the decreased pulpal blood flow (by approximately 43%) that occurs some six minutes after mandibular block anesthesia using 2% lidocaine with epinephrine 1:100,000.[19]

A previous study has reported that an increase of 5.5°C within the pulp chamber caused irreversible damage in 15% of healthy rhesus monkey teeth.[4] Below this value, the pulp can recover, but there are some small histological damages. In an *in vitro* study, LCUs that were analyzed in the presence of simulated pulpal fluid flow did not produce a temperature rise within the pulp chamber above the critical point of 6°C.[7] Similar results have been shown in other studies using different LCUs with different light-curing modes.[10,34] As in the present study, as a result of the effect of the water flow in the interior of the chamber, the two LCUs tested proved to be safe to use. However, in the absence of pulpal microcirculation, the temperature increase within the pulp could be harmful to the pulp,[7] especially when the LCU delivered an irradiance above 1000 mW/cm^2.[36] In a previous study, without microcirculation a thin layer of the adhesive system was unable to block the heating produced by LCU and produced a temperature increase that was above the critical point.[24] The present study confirmed that without a simulated pulpal microcirculation, when the adhesive system was light cured with Bluephase G2 for 20 seconds, the temperature rise could become critical.

Although studies have evaluated the effect of the restorative procedures on changes in the pulp temperature,[15,36] few studies have simulated the microcirculation when collecting these values.[6,7,34] The presence of pulpal microcirculation and pressure in the teeth tested better simulates the real clinical condition.[7] However, *in vitro* experimental studies always have limitations, and further studies are necessary to determine the effect of a simulated microcirculation in the pulp on the thermal control of the oral environment. Another limitation of this study is that the dentin thickness was only estimated from two-dimensional radiographs; the remaining dentin thickness could be better evaluated using three-dimensional methods.

To the knowledge of the authors, there is no other equipment available on the commercial market that combines the three factors of flow, pressure, and temperature all in the same apparatus. This combination allows clinical conditions to be better studied under *in vivo* conditions in the laboratory, and it could also be used in other biomechanical tests, such as measuring the shrinkage strain or bond strength testing.

CONCLUSIONS

Within the limitations of this study, we conclude that simulating microcirculation in the pulp can help to dissipate the heat generated when light curing resins, resulting in a lower temperature increase. The temperature rise was greatest when the adhesive system was light cured for 20 s (4 to 6°C without any microcirculation) and lower when the 4-mm-thick bulk fill resin composites were photocured for 20 or 40 s which produced a temperature increase of approximately 3°C when there was no microcirculation present.

The flowable bulk fill resin (SDR) used in this study produced a greater exothermic reaction, allowed more light transmission (18.3% for VALO Cordless and 23.3% for Bluephase G2), and achieved a higher DC at the bottom of 4 mm compared to the AURA composite. Although the Bluephase G2 always delivered a higher irradiance, the VALO Cordless produced a higher DC at the bottom surface of the two resin composites tested.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Ethics Committee in Human Research of Federal University of Uberlandia. The approval code for this study is: 1.451.872.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article

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