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Temperature Increase at the Light Guide Tip of 15 Contemporary LED Units and Thermal Variation at the Pulpal Floor of Cavities: An Infrared Thermographic Analysis

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Clinical Relevance

The thermal variation at the pulpal floor of dental cavities during photopolymerization is associated with the measured irradiance level of LED curing units.

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SUMMARY

In this study, a comprehensive investigation on the temperature increase at the light guide tip of several commercial light-emitting diode (LED) light-curing units (LCUs) and the asso-

ciated thermal variation (ΔT) at the pulpal floor of dental cavities was carried out. In total, 15 LEDs from all generations were investigated, testing a quartz-tungsten-halogen (QTH) unit as a reference. The irradiance level was measured with a power meter, and spectral distribution was analyzed using a spectrometer. Temperature increase at the tip was measured with a type-K thermocouple connected to a thermometer, while ΔT at the pulpal floor was measured by an infrared photodetector in class V cavities, with a 1-mm-thick dentin pulpal floor. The relationship among measured irradiance, ΔT at the tip, and ΔT at the pulpal floor was investigated using regression analyses. Large discrepancies between the expected and measured irradiances were detected for some LCUs. Most of the LCUs showed an emission spectrum narrower than the QTH unit, with emission peaks usually between 450 and 470 nm. The temperature increase at the tip followed a logarithmic growth for LCUs with irradiance ≥1000 mW/cm², with ΔT at the tip following the measured irradiance linearly (R^2=0.67). Linear temperature increase at the pulpal floor over the 40-second exposure time was observed for several LCUs, with linear association between ΔT at the pulpal floor and measured irradiance (R^2=0.39) or ΔT at the tip (R^2=0.28). In conclusion, contemporary LED units show varied irradiance levels that affect the temperature increase at the light guide tip and, as a consequence, the thermal variation at the pulpal floor of dental cavities.

INTRODUCTION

Dental dimethacrylate-based restorative composites polymerize via free-radical polymerization under irradiation with visible light. Development of the polymerization reaction is influenced by many factors related to the composite, such as comonomer formulation,[1-4] shade,[5] translucency,[6] and filler loading/size,[7] as well as to the curing unit, such as irradiance level,[8-10] exposure time,[11,12] emission spectrum,[13] and thermal variation.[14,15] Sufficient light energy reaching the composite is necessary to ensure adequate polymerization; the spectral irradiance of the light also has to overlap as much as possible the absorption spectrum of the photosensitizer contained in the material, that is, camphorquinone (CQ).[3,4]

Blue light-emitting diodes (LEDs) were introduced to overcome shortcomings of the traditional quartz-tungsten-halogen (QTH) light-curing units (LCUs). LEDs consume little power in operating and do not require filters to produce blue light. The main difference in the emission radiation is the narrower spectrum of wavelengths of the LEDs, usually centered on 470 nm, which is the wavelength at which CQ has its maximum energy absorption.[16] The semiconductors used for light emission in LEDs, instead of the hot metal filaments in QTH bulbs, generate less internal heating and undergo little degradation over the course of the time. First-generation LEDs emitted low irradiance, hence they generated low heat and were considered "cold-light devices." However, as high-irradiance, second- and third-generation LEDs were introduced, the increase in irradiance was associated with a thermal increase.[9]

It has been reported that external heating may enhance the conversion kinetics of resin composites and increase the network cross-linking.[14,15] Increased temperature may enhance the mobility of reactive species during polymerization, ultimately resulting in further conversion. Therefore, LCUs with low irradiance levels, despite tending to reduce the heat generation, could pose a risk to increased cytotoxicity and poorer mechanical properties of the restorative due to lower conversion. There is also a controversial issue regarding the critical temperature increase that may cause injury to the dental pulp. Zach and Cohen[17] reported that an increase of 5.5°C within the pulp chamber caused irreversible damage to monkey teeth. Another investigation, however, showed that a temperature increase of 11.2°C did not damage the pulp.[18] Laboratory studies usually analyze the temperature variation at the light guide tip of the LCU, but the thermal variation (ΔT) yielded at the pulpal floor or chamber[19,20] is probably more relevant as regards the biological issues related to high-irradiance curing units.

The aim of the present study was to provide a comprehensive investigation on the temperature increase at the light guide tip of commercially available LED LCUs and the associated ΔT at the pulpal floor of class V dental cavities during photopolymerization procedures. In total, 15 LEDs from all generations were investigated, testing a QTH unit as a reference. The hypothesis tested was that increased temperature at the light guide tip of the LCUs would be associated with increased ΔT at the pulpal floor of the cavities.

MATERIALS AND METHODS

LED Units Tested, Irradiance, and Emission Spectrum

Fifteen commercial LED units were tested, as shown in Table 1. The conventional QTH unit Optilux 501 (Kerr, Orange, CA, USA) was tested as a reference. The units (when applicable) were fully charged before testing. The irradiance level of each unit was measured five times with a calibrated power meter (Ophir Optronics, Jerusalem, Israel), and the spectral distribution was analyzed using a computer-controlled spectrometer (USB2000, Ocean Optics, Dunedin, FL, USA). The radiant exposure was calculated on the basis of a 40-second exposure time.

Temperature Increase at the Light Guide Tip

Measurements were carried out under controlled temperature (25°C) and humidity (45%) conditions using a type-K thermocouple (Salcas, São Paulo, SP, Brazil) connected to a digital thermometer accurate to 0.1°C, with 0.1-second response time. After calibration in water baths with temperatures ranging between 25°C and 40°C, the thermocouple was positioned in contact with the light guide tip. The temperature was recorded every 5 seconds during the total 40-second exposure time.

ΔT at the Pulpal Floor

The lingual faces of 150 bovine incisors were removed. Standard class V cavities (2.5 mm wide × 3 mm long) were prepared 1 mm above the cemento-enamel junction in the buccal faces using water-cooled #3099 cylindrical diamond burs (KG Sorensen, Barueri, SP, Brazil) in a high speed handpiece. Burs were replaced after every four preparations. The cavity depth was controlled in order to standardize a 1-mm dentin thickness at the pulpal floor of all cavities. The teeth were held in position using a custom-made device, and temperature at the pulpal floor was measured by infrared thermographic analysis using a handheld quantum well infrared photodetector (ThermaCAM SC 3000, FLIR Systems Inc, Boston, MA, USA) with 0.01°C accuracy and 0.01-second response time. The thermographic camera was directed to the pulpal chamber through the exposed lingual face of the teeth at a 10-cm distance between the sample and camera. The camera was calibrated considering the dentin emissivity to be 0.91 within the temperature range of 20°C to 100°C,[21] with data acquisition at 60 Hz. Measurements were carried out under controlled temperature (25°C) and humidity (45%) conditions. The LED units were placed in contact with the buccal aspects of the teeth, and light exposure was carried out for 40 seconds (n=10); data were processed using the software ThermaCAM Research 2001 (FLIR Systems Inc).

Statistical Analysis

Data for ΔT measured by the thermocouple/thermometer setup and ΔT data from the thermographic analysis were separately submitted to one-way analysis of variance followed by the Tukey's *post hoc* test. The relationship among measured irradiance, ΔT at the light guide tip, and ΔT at the pulpal floor was investigated using linear regression analyses. All analyses were conducted at a 5% significance level.

RESULTS

Irradiance, Energy Dose, and Emission Spectrum

Table 1 shows the characteristics of the LCUs tested. In order to facilitate comparisons, the LCUs were separated into four groups. Large discrepancies between the expected and measured irradiance levels were detected for most of the LCUs, especially those with measured irradiance <800 mW/cm^2. Results for the calculated energy dose are shown in Table 2; a wide range between 8 and 48 J/cm^2 was calculated. The spectral distribution of the lights is shown in Figure 1. Most of the LCUs showed an emission spectrum narrower than the QTH unit (OPL), with emission peaks usually centered on the range between 450 and 470 nm.

Temperature Increase at the Light Guide Tip

Figure 2 shows the profiles of temperature increase at the tip over the 40-second exposure time. Results for ΔT at the tip are shown in Table 2. The statistical analysis showed significant differences among the groups (p<0.001). The LCUs with measured irradiance >800 mW/cm^2 showed significantly higher ΔT at the tip than the LCUs with lower irradiance levels. The QTH unit (OPL) showed significantly higher ΔT than all LED units with irradiance ≤800 mW/cm^2. The ΔT profiles followed a logarithmic growth pattern for the LCUs with irradiance ≥1000 mW/cm^2.

ΔT at the Pulpal Floor

Figure 3 shows the profiles of temperature increase at the pulpal floor over the 40-second exposure time; a linear temperature increase was observed for

Table 1: *Characteristics of the Light-Curing Units (LCUs) Tested*

LCU	Manufacturer	Code	Emission Mode	Expected Irradiance,[a] mW/cm^2	Measured Irradiance, mW/cm^2
LCUs<450 mW/cm^2					
Ultra Blue IV Plus	DMC, São Carlos, SP, Brazil	UTB	Continuous	600	200
Biolux	Bioart, São Carlos, SP, Brazil	BIO	Soft-start	300 (5 s)/1000 (35 s)	200 (5 s)/400 (35 s)
Radii Plus	SDI, Bayswater, Victoria, Australia	RDP	Continuous	1500	410
Optilux 501 (QTH)	Demetron Kerr, Orange, CA, USA	OPL	Continuous	850	448
LCUs<800 mW/cm^2					
LEC 470 II	MM Optics, São Carlos, SP, Brazil	LEC	Continuous	400	475
Mais	Mais, Ribeirão Preto, SP, Brazil	MAI	Continuous	700	500
UltraLight III	Sanders Medical, S. R. Sapucaí, MG, Brazil	UTL	Soft-start	1200	200 (5 s)/600 (35 s)
Elipar Freelight 2	3M ESPE, St. Paul, MN, USA	EFL	Continuous	1200	795
LCUs≤1000 mW/cm^2					
LEDemetron	Demetron Kerr	LDM	Continuous	800	800
Smart Lite PS	Dentsply Caulk, Milford, DE, USA	SML	Continuous	950	995
Celalux	Voco, Cuxhaven, Germany	CEL	Continuous	1000	1000
Ultra-Lume LED 5	Ultradent, South Jordan, UT, USA	ULM	Continuous	800	1000
LCUs>1000 mW/cm^2					
Demi	Demetron Kerr	DEM	Pulsatile	1100	1015
Bluephase	Ivoclar Vivadent, Schaan, Liechtenstein	BLP	Continuous	1200	1180
Blue Star I	Microdont, São Paulo, SP, Brazil	BST	Continuous	1000	1200
FLASHlite 1401	Discus Dental, Culver City, CA, USA	FLH	Continuous	1400	1200

[a] *As provided by the manufacturer.*

Table 2: *Means (SD) for Energy Dose, Thermal Variation (ΔT) at the Tip, and ΔT at the Pulpal Floor*

LCU	Energy Dose,[a] J/cm^2	ΔT (Tip), °C	ΔT (Pulpal Floor), °C
LCUs<450 mW/cm^2			
UTB	8	3.8 (0.1) H	2.4 (0.04) H
BIO	15	4.6 (1.6) H	3.4 (0.02) GH
RDP	16.4	7.1 (0.1) GH	5 (0.08) EFG
OPL (QTH)	17.9	15.3 (0.8) E	6.3 (1.8) CDEF
LCUs<800 mW/cm^2			
LEC	19	9.8 (0.3) FG	4.7 (0.09) FG
MAI	20	9.3 (0.3) GH	3.9 (0.06) GH
UTL	22	7.8 (0.4) GH	3.4 (0.9) GH
EFL	31.8	12.1 (0.2) FG	4.9 (0.1) EFG
LCUs≤1000 mW/cm^2			
LDM	32	12 (1.0) FG	6.7 (1.17) CDE
SML	39.8	22 (0.8) D	11.3 (0.07) A
CEL	40	21.6 (0.8) D	4.9 (0.09) FG
ULM	40	38.8 (0.5) B	9 (1.7) AB
LCUs>1000 mW/cm^2			
DEM	40.6	28 (5.9) C	2.3 (0.12) H
BLP	47.2	20 (0.3) D	10.6 (0.15) BC
BST	48	26.5 (0.3) C	7.2 (0.12) CD
FLH	48	45 (2.0) A	7.7 (0.13) ABC

[a] *Calculated on the basis of a 40-second exposure time. In each column, distinct letters indicate significant differences (*$p<0.05$*).*

several LCUs. Except for OPL (QTH), none of the LCUs with measured irradiance up to 800 mW/cm^2 showed maximum temperature increase above 5.5°C, while only CEL showed maximum temperature increase below 5.5°C for the LCUs with measured irradiance >800 mW/cm^2. Results for ΔT at the pulpal floor are shown in Table 2. The statistical analysis showed significant differences among groups ($p<0.001$). Similarly to the ΔT at the light guide tip, the LCUs with measured irradiance >800 mW/cm^2, except for CEL and DEM, showed significantly higher ΔT at the tip than the LCUs with lower irradiance levels.

Linear Regression Analyses

Regression plots are shown in Figure 4. It was observed that ΔT at the light guide tip of the LCUs follows linearly the measured irradiance ($R^2=0.67$; $p<0.001$) and ΔT at the pulpal floor ($R^2=0.28$; $p=0.04$). The relationship ΔT the pulpal floor and measured irradiance is also linear ($R^2=0.39$; $p<0.01$).

DISCUSSION

The present results indicate that large discrepancies between the expected and measured irradiance levels emitted by some LED LCUs were observed. The measured irradiances were, sometimes, less than one-third the irradiance the manufacturers originally claimed. This evidence reinforces the fact that clinicians should be cautious about manufacturers' claims. Each resin composite has a minimum light exposure time indicated for proper polymerization, and clinicians tend to follow this time; however, shorter exposure times could sound reasonable when high-intensity units are used. A way to avoid problems is to always check the irradiance level of the LCUs, regardless of the manufacturers' claims, and always follow the photoactivation time indicated for the composite. The present results show that the energy doses calculated based on a 40-second photoactivation time also varied significantly, although the radiant exposure calculated for most of the LCUs was above 20 J/cm^2. Care should be taken again because a 40-second exposure time is usually twice the time indicated for most of the resin composites available in the market, and very low radiant exposures could be delivered by some LCUs in shorter photoactivation times. In addition, it has been reported that the irradiance delivered from LCUs is not uniform across the light tip,[22] which may also hinder calculation of energy doses applied to the restorative materials.

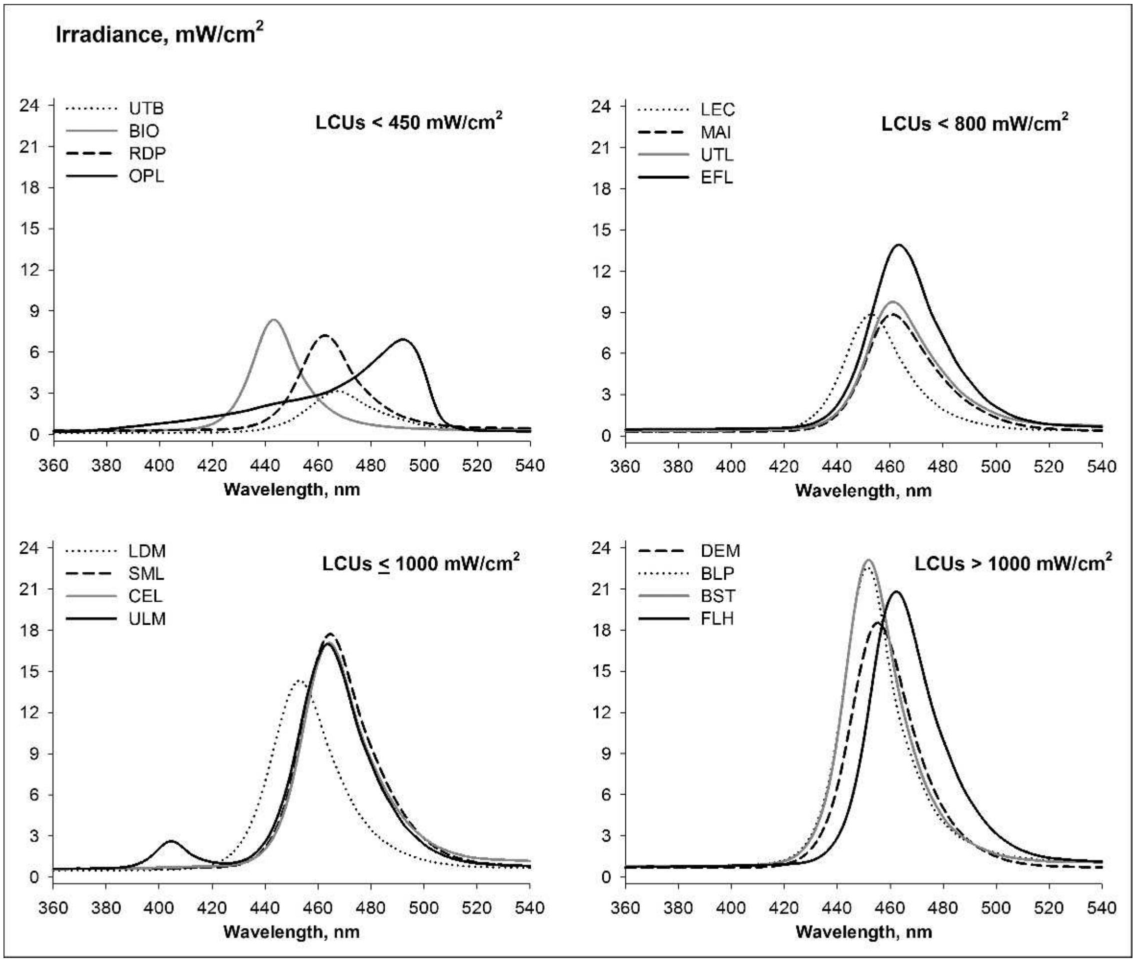

Figure 1. *Spectral emission of the light-curing units (LCUs) tested: Ultra Blue IV Plus (UTB), Biolux (BIO), Radii Plus (RDP), Optilux 501-QTH (OPL), LEC 470 II (LEC), Mais (MAI), UltraLight III (UTL), Elipar Freelight 2 (EFL), LEDemetron (LDM), Smart Lite PS (SML), Celalux (CEL), Ultra-Lume LED 5 (ULM), Demi (DEM), Bluephase (BLP), Blue Star I (BST), and FLASHlite 1401 (FLH).*

The light spectral emission of the LEDs tested was usually centered on the 450- to 470-nm range, with narrower emission distribution compared with the QTH unit. This is important information because efficient correlation between the light spectral irradiance and the absorption spectrum of the photosensitizer contained in the restorative may overcome problems related to low light irradiance levels.[19] It is known that free-radical polymerization of methacrylates, among other factors, is dependent on the number of photons available in the area around the peak of major absorption of the photosensitizer (for CQ, at 468 nm).[16] Variation in radiant exposure may significantly impact the polymerization kinetics of photoactivated restoratives as well the mechanical properties of the resulting polymer.[11]

Regarding the thermal variation results, the ΔT at the light guide tip of the LCUs was linearly associated with the measured irradiance of the LCU. This is explained by the fact that higher light power outputs are associated with increased generation of radiation energy. Compared with the QTH, 7 out of the 15 LEDs tested yielded significantly higher temperature increase at the tip device. This indicates that LEDs used for dental light-curing purposes might not be considered "cold-light devices" as a general rule. For some LEDs, the temperature increase at the tip was 153% to 194% higher than the QTH unit. The temperature increase showed a logarithmic growth for LCUs with irradiance $\geq$1000 mW/cm^2, indicating that the heat generated is not dissipated by the LCU itself.

The ΔT results at the pulpal floor provided additional evidence that dental LEDs generate high thermal energy. Only two LEDs from the eight units that presented irradiance $\geq$800 mW/cm^2 generated temperature increase below 5.5°C, which here is used as a reference based on the work by Zach and

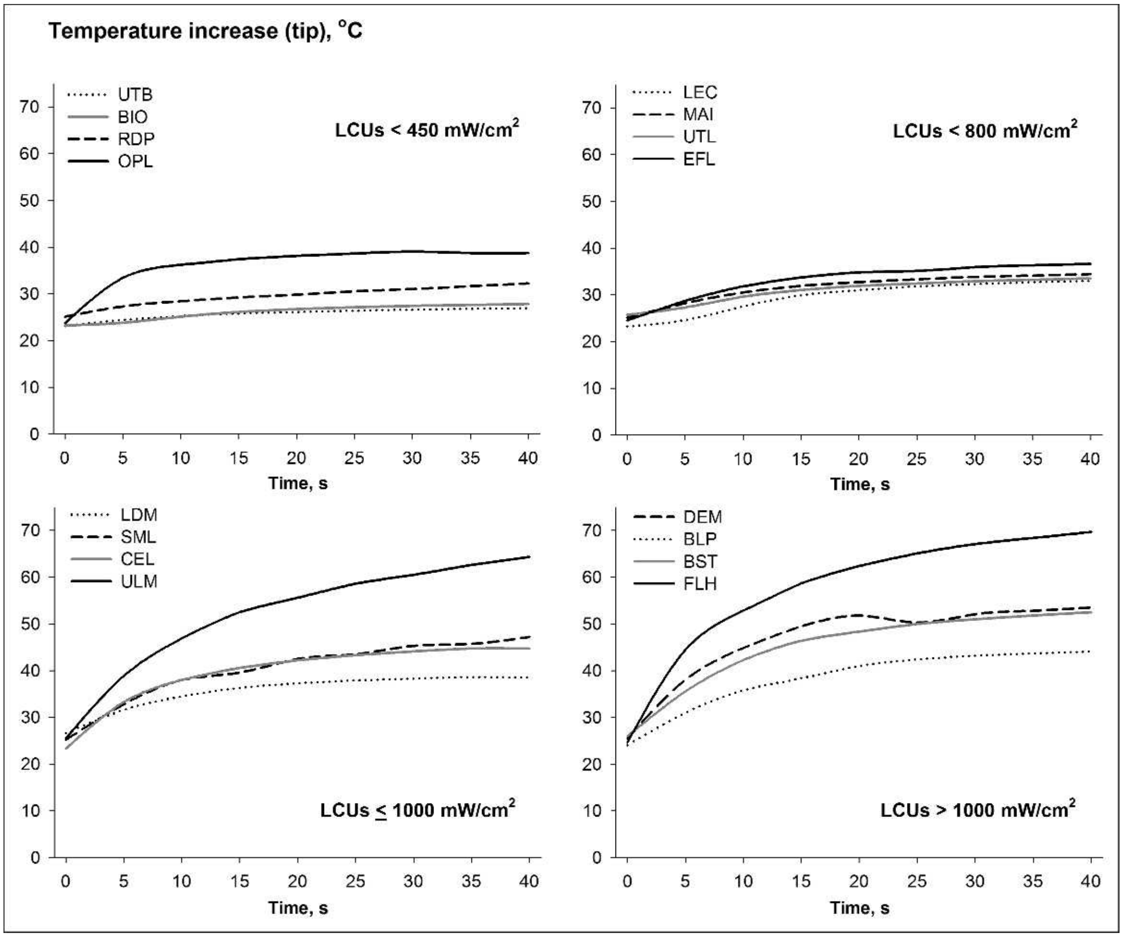

Figure 2. *Profiles of temperature increase at the light guide tip over the 40-second exposure time. The temperature increase followed a logarithmic growth pattern for the LCUs with irradiance ≥1000 mW/cm².*

Cohen.[17] An interesting result was found for DEM, which emits a pulsatile light; despite the high ΔT at the tip of this LCU, the ΔT at the pulpal floor was below most of the other LCUs. This is explained by the intermittent light exposure allowing more time for the heat to dissipate by the tooth structure. In spite of this example, the ΔT at the pulpal floor of cavities followed linearly both the measured irradiance of the LCU (R^2=0.39) and ΔT at the light guide tip (R^2=0.28). Therefore, the hypothesis tested is accepted. As the irradiance level can be measured clinically with a radiometer, despite its inaccuracy as sometimes reported,[23] and the correlation between irradiance and ΔT at the pulpal floor was linear for both the measured irradiance of the LCU (R^2=0.39) and ΔT at the light guide tip (R^2=0.28), the measured irradiance of the LCU might be taken as a feasible tool to predict the ΔT at the pulpal floor during photopolymerization procedures. The methods used here, however, have limitations, such as the absence of pulpal fluid perfusion, use of bovine teeth, and baseline temperatures below the intraoral temperature, and these should also be taken into account when extrapolating the results.

The present study was not focused on determining critical temperature levels that may be harmful to the pulpal tissues. For instance, the results reported by Zach and Cohen[17] that an intrapulpal temperature rise above 5.5°C might cause pulp cell vitality injuries difficult to recover are for a sustained temperature increase, but the temperature increases during light-curing procedures are relatively brief. The focus of the present study was rather to conduct a comprehensive investigation of several LED LCUs available on the market and investigate the relationship of irradiance level and thermal variations. When the remaining dentin is thick (ie, in shallow to medium cavities), light scattering may predominate over light absorption because the dentin absorption coefficient is low for the wavelengths emitted by dental LCUs.[24] Special concern lies for bonding procedures in deep cavities, where photoactivation

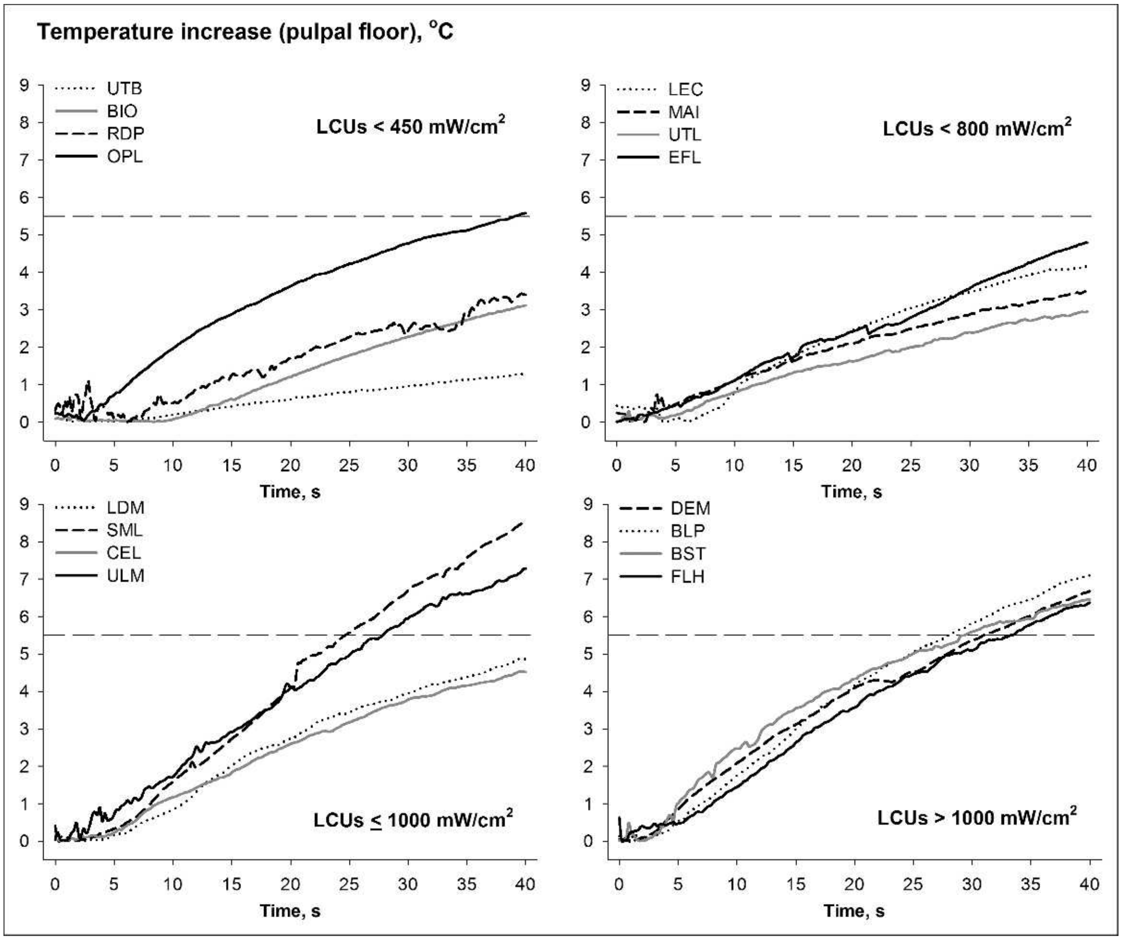

Figure 3. *Profiles of temperature increase at the pulpal floor over the 40-second exposure time. Data are shown not taking into account the baseline temperature (25°C) in order to allow observation of the maximum temperature increase compared with the 5.5°C used as a reference.*[17] *A linear increase was observed for several LCUs.*

of the adhesive is carried out without any layer of restorative resin that could act as a barrier for thermal conduction.[19,25]

Clinicians should be familiar with the factors that are involved in temperature increase during photoactivation procedures in dental cavities, especially the irradiance level emitted by the LCU and the thickness of the remaining dentin. As the temperature at the pulpal floor increases linearly over the exposure time for several LCUs, clinicians should be aware of the possibility of overheating the area when using prolonged photoactivation protocols,[20] especially during the initial restorative steps, when the dentin is more exposed. An alternative to reduce the thermal increase at the pulpal floor in deep cavities could be the use of a glass-ionomer base, but the presence of such a base may decrease restoration survival compared with total-etch restorations.[26,27] Therefore, clinical studies investigating the survival and postoperative sensitivity of composite restorations performed using different LCUs are still necessary.

CONCLUSION

Within the limitations of the present study, the following conclusions can be drawn:

- Large discrepancies between the irradiance emitted by some LED units and the irradiance level claimed by the manufacturers were observed.
- The thermal variation at the light guide tip followed a logarithmic growth pattern for units with irradiance $\geq$1000 mW/cm^2, while a linear temperature increase at the pulpal floor was observed for several units.
- The measured irradiance of LED units was linearly associated with the thermal variation at the pulpal floor of dental cavities during photopolymerization.

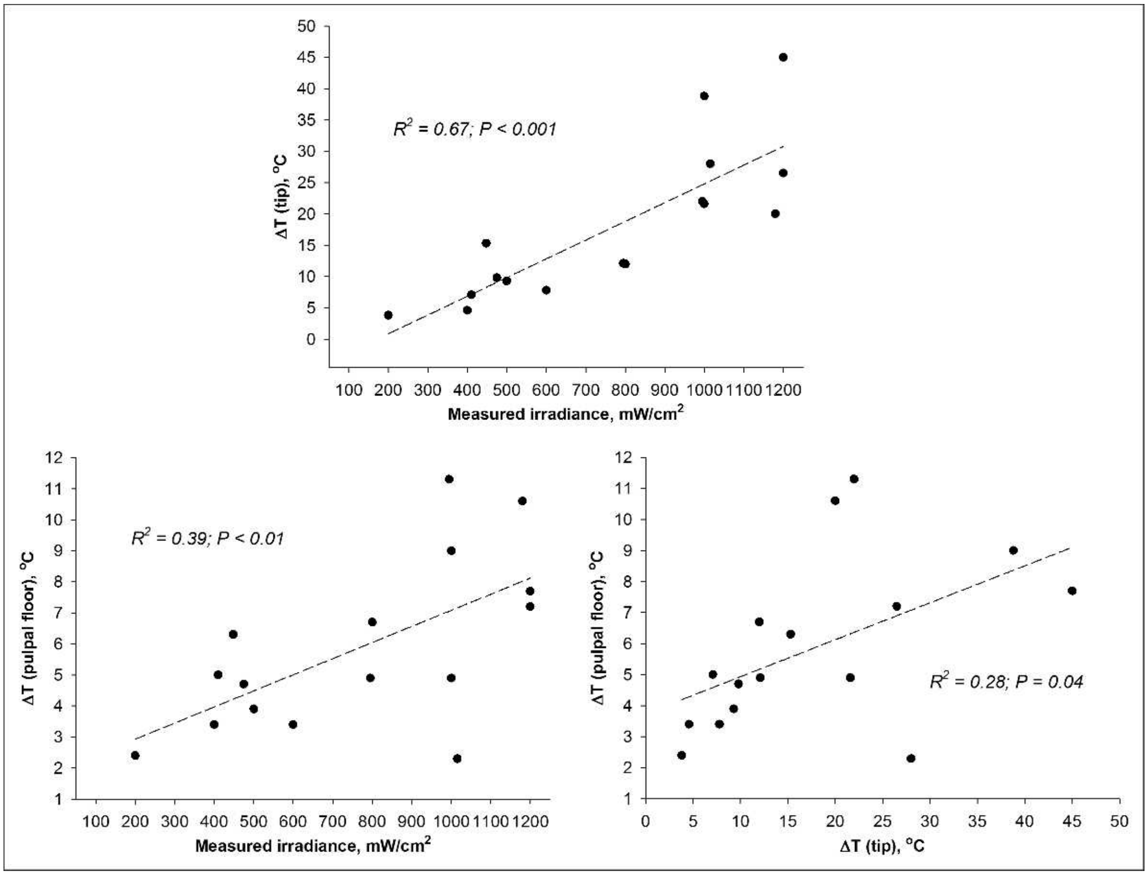

Figure 4. *Regression plots showing that the thermal variation (ΔT) at the light guide tip follows linearly the measured irradiance of the LCUs (R^2=0.67; p<0.001) and ΔT at the pulpal floor (R^2=0.28; p=0.04); the relationship ΔT the pulpal floor and measured irradiance is also linear (R^2=0.39; p<0.01).*

Conflict of Interest

The authors of this article 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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