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Pulpal-temperature Rise and Polymerization Efficiency of LED Curing Lights

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Clinical Relevance

This paper provides practitioners with useful information on the importance of aligning the spectra of the LCU and the material in terms of polymerization efficiency and temperature rise in the pulp chamber.

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SUMMARY

This paper assesses the effects of light characteristics and irradiation time on the Vickers microhardness (VH) of a dual-photoinitiator commercial composite and on temperature increase in the pulp chamber (ΔT). Four recent light-emitting diodes (LEDs)—bluephaseG2 (BG2), bluephase16i (B16i), G-Light (G) and Freelight2 (F2)—and one control halogen light (XL3000–X) were tested on two shades of Tetric EvoCeram (A2 and Bleach XL), whose respective commercial formulations differed based on their concentration of camphorquinone and lucirin TPO. Three different irradiation times were applied— 10, 20 and 40 seconds—and VH was measured on the upper and lower surfaces of 2-mm thick samples. The ΔT was measured by using a K-type thermocouple inserted into the pulp chamber of a molar that had been prepared to obtain a 2-mm thickness of dentin. The measurements were made either during polymerization of a 2 mm composite (Shade A2

or Bleach) or with an empty mold. The data were analyzed with the two-way ANOVA ($p<0.05$) test. For shade A2, all but one irradiation condition (F2–10 seconds, lower surface) generated VH values that were statistically equal to or better than the standard chosen for this study (X–40 seconds). For Bleach shade, the VH values obtained with G and BG2–20 and 40 seconds were statistically comparable to X–40 seconds for both the upper and lower surfaces. This was not the case with either G and BG2–10 seconds or for all the procedures with other LCUs for which a VH of at least one of the surfaces was significantly lower than the reference. The results also highlight differences between the two material shades, whether the upper or lower surface is considered. Regarding temperature measurements for shade A2, B16i–20-40 seconds, BG2–40 seconds and G–40 seconds induced significantly higher ΔTs (3.98, 5.98, 5.21 and 4.95, respectively) than X–40 seconds (3.09). For Bleach shade, B16i–20 and 40 seconds, F2–20 and 40 seconds, BG2–40 seconds and G–40 seconds generated ΔTs significantly higher than the control values (2.70, 4.05, 3.03, 4.58, 2.74 and 2.44, respectively). The ΔT values obtained with uncovered tooth were generally higher than those obtained with a 2-mm layer of composite. In conclusion, this research emphasizes that a perfect correspondence between light and material spectra is of prime concern, both to insure optimal polymerization and to limit heating in the pulp chamber. Some reduction in curing time is possible, but only within certain limits.

INTRODUCTION

Since the introduction of photopolymerizable dental composites, various technologies have been proposed for light-curing units (LCU): Initially, UV-lights were developed, then visible-light systems, such as quartz-tungsten halogen (QTH) lights, plasma-arc curing units, lasers, and more recently, light-emitting diodes (LEDs). Among the different light-curing systems available today, LEDs seem to present the best technology for several reasons: their narrower spectrum is better centered on the peak of maximum absorption of the main composite photoinitiator, camphorquinone (CQ), which increases irradiation efficiency.[1] Second, the low power consumption of LED LCUs enables the use of batteries, which have led to significant ergonomic improvement[2] and smaller, better-adapted fans or other heat dissipating devices. While first generation LED lights did not meet with general approval due to their low power density,[2-3] new generation lights are now increasingly used by practitioners. These newer LED lights have been shown to have produced material properties similar to QTH lights.[4-5] Moreover, several publications have highlighted the potential of these lights as reducing irradiation time without a significant loss of mechanical properties.[4,6-7]

Recently, with the emergence of tooth whitening, extra-white composites have been developed to match very light shades, which were difficult to achieve with CQ/amines because of their yellowish aspect. For this reason as well as to improve photoinitiation efficiency, alternative photoinitiators, such as phenylpropanedione (PPD), monoacylphosphine oxide (MAPO or lucirin TPO) and bisacylphosphine oxide (BAPO or Irgacure 819), have been studied and some have been introduced into composites. However, the absorption spectra of these molecules are different from the CQ spectrum. The narrow spectrum of blue LED lights, initially recognized as an asset, can therefore become a problem, because of incompatibility with these alternative photoinitiators.[8] To overcome this problem, the so-called "third generation" of LED LCUs was created, combining two different light peaks, one blue and one violet. Initial results achieved with these lights have been promising, because they are similar to or better than those achieved with second generation LED LCUs.[9]

Given the lack of information from manufacturers about the photoinitiating systems of commercially available composites, dentists face a difficult choice from all the diverse light-curing systems. Compared to halogen LCUs, LED LCUs have two main assets (in addition to ergonomy)—reduction in tooth heating and irradiation time. Regarding heat reduction, this asset was already present in the first generation of LED lights, probably as a result of their lower power density. Asmussen and Peutzfeldt[10] showed that temperature rise was correlated with power density. Similarly, Vandewalle and others[11] observed a similar increase in pulpal temperature between an LED and a halogen LCU of the same power density. As a result, because the power densities of recent LED lights are comparable to or higher than that of QTH lights, the temperature rise in the pulp chamber can be similar or higher.[12-13] In a recent paper, Antonson and others[2] proposed that the effects of heat generated by new, high powered LED LCUs need to be determined. In addition, as demonstrated by Schneider and others,[3] temperature rise is important when evaluating the curing efficacy of new lights. This is true both from a safety viewpoint[2,13] and in terms of curing efficacy, as temperature increase can enhance polymer properties.[14-15] With regard to curing time, the better match between absorption/emission spectra and the higher power density of recent LED LCUs enables a reduction in curing time, sometimes down to 20 or even 10 seconds.[7] Shortall[4] and Yap and Soh[6] also demonstrated the potential for a second generation LED to be as effective as a halogen LCU, with a 50% reduction in curing time. However, several authors have also stressed that the ability of an increase in power density to compensate for time reduction is limited.[16-18] Notably, Peutzfeldt and Asmussen[16] showed that, for a given energy density, when power density was increased, the degree of conversion decreased linearly; whereas, flexural strength and flexural modulus showed a parabolic relationship.

Therefore, the current study had two main objectives. The first was to evaluate the polymerization efficiency of 10-, 20- and 40-second irradiations with four recent LED lights (two single peak, "second-generation" LEDs and two multiple peak, "third-generation" LEDs) on two variants of the same composite, Tetric Evo Ceram shade A2 and shade Bleach XL (Ivoclar Vivadent, Schaan, Liechtenstein). These materials were chosen for their different photoinitiating systems—both contain camphorquinone (CQ) and lucirin-TPO (L) in different ratios. In shade A2, CQ is dominant, while in Bleach shade, L is present in greater concentrations.[19] A standard photoinitiation method commonly accepted for the polymerization of 2 mm composites was chosen for the comparison: Conventional halogen light for 40 seconds.[15-16] The second purpose of this study was to analyze the thermal effect of the different irradiation conditions on the pulp chamber. Hence, this research aimed to determine the interaction between pulpal temperature rise and composite hardness using different recent LED LCUs.

METHODS AND MATERIALS

Spectrum Characterization

Five different lights were used. A conventional halogen light was chosen as the control and was compared to four LED lights. The lights are presented in Table 1. The spectra of the five lights were determined by a mini-spectrometer (RC series C9407MA, Hamamatsu, Japan) and their irradiance was determined by five measurements with a bluephase meter (Ivoclar Vivadent). As both composite shades chosen for this study contain two photoinitiators (CQ and L) in different proportions, the absorption spectra of both pure photoinitiators was recorded using a UV-vis-NIR spectrophotometer (Cary 500, Varian, Inc, Palo Alto, CA, USA).

Curing Efficacy

Two shades of the composite Tetric Evo Ceram (Ivoclar-Vivadent), A2 and Bleach XL, were chosen for this study. This choice was based on differences in their photoinitiating mix. The samples were prepared according to the following procedure: The composite was placed in a cylindrical brass mold 3 mm in diameter and 2 mm in depth, covered by a thin Mylar film, then light-cured from the upper surface.

Each LCU was applied to photopolymerize samples of both shades for three irradiation times (10, 20 and 40 seconds). Five samples were prepared for each light/time/shade combination. As microhardness is correlated with the degree of conversion,[20-21] polymerization efficacy was assessed by measurement of the Vickers microhardness on the upper and lower surfaces of each sample as follows: a 200 g load was applied for 30 seconds to the upper surface using a Durimet microhardness tester (Leitz, Wetzlar, Germany). The length of the diagonal of each inden-

Table 1: *Tested Lights*

Name	Code	Manufacturer	Light Type	Mode*	Expected Irradiance (mW/cm²)	Measured Irradiance (mW/cm²)	Recommended Curing Time** ***
bluephase 16i	B16i	Ivoclar-Vivadent (Schaan, Liechtenstein)	LED 2nd generation	High	1600 +/-100	1622 (+/-78)	10 seconds
bluephase G2	BG2	Ivoclar-Vivadent (Schaan, Liechtenstein)	LED 3rd generation	High	1200 +/-10%	1050 (+/-14)	10 seconds
G-Light	G	GC Corporation (Tokyo, Japan)	LED 3rd generation	-	1200 (+/-78)	1166	10 or 20 seconds
Freelight 2	F2	3M ESPE (St Paul, MN, USA)	LED 2nd generation	-	1000	644 (+/-26)	50% reduction vs conventional halogen
XL3000	X	3M ESPE (St Paul, MN, USA)	Halogen	-	data not found	544 (+/-17)	40 seconds

**When choice possible between Low & High power mode*
***Based on information from the manufacturer*
****For 2 mm micro-hybrid composite, at high power when different modes available*

tation was measured directly using a graduated eye lens. The Vickers Hardness Number (VHN) was obtained using the following equation: $H = 1854.4 \times P/d^2$, where H is Vickers hardness in kg/mm², P is the load in grams and d is the length of the diagonal in µm. Note that a null VHN refers to a material too soft to record any value.

Temperature Rise in the Pulp Chamber

A K-type thermocouple was used to monitor the thermal changes in the pulp chamber. The thermocouple measured a potential difference (mV), depending on the temperature difference. Using a converter (Omega Engineering Inc, Stamford, CT, USA), the potential difference was recorded and transformed into a temperature differential (ΔT) in degrees Celsius (°C) according to the following equation: $\Delta T = a_1 (V-V_r) + a^2 (V^2-V_r^2)$, where a_1 and a_2 are constants, V is the potential difference (mV) at a given time of the measurement and V_r is the potential difference (mV) before measurement when the immersion water is at room temperature.

The thermocouple was inserted into the pulp chamber of an extracted molar that had been prepared according to the following procedure: after extraction, the tooth was stored in chloramine (0.1% NaCl in purified water). The major part of the root was ground away and the remains of the pulpal tissue were removed. The occlusal face of the tooth was also ground in order to keep 2 mm of dentin between the upper surface and the thermocouple (Figure 1). During measurements, the tooth was immersed in water at ambient temperature (23 ± 1°C), so that the pulp chamber was completely filled with water in order to simulate the liquid environment of the pulpal tissues. All the measurements were performed with the same tooth to limit any effects of differences in tooth structure, thus enabling the study to concentrate on differences between the lights. Before each measurement, a Teflon mold (2 mm-thick with a 4 mm-diameter aperture) was placed on the upper tooth surface that had been dried, using a cotton pellet. The increase in temperature during irradiation of the tooth through the aperture for 40 seconds with each of the five lights, as described in Table 1, was measured. These temperature measurements were performed with an empty cavity and when the cavity was filled with composite, either shade A2 or Bleach. As no adhesive system was used, the composite could easily be removed after each measurement without leaving any significant deposit on the surface. The temperature was recorded during irradiation and the measurement was extended until ambient temperature (23 ± 1°C) had been regained. The procedure was repeated three times for each combination.

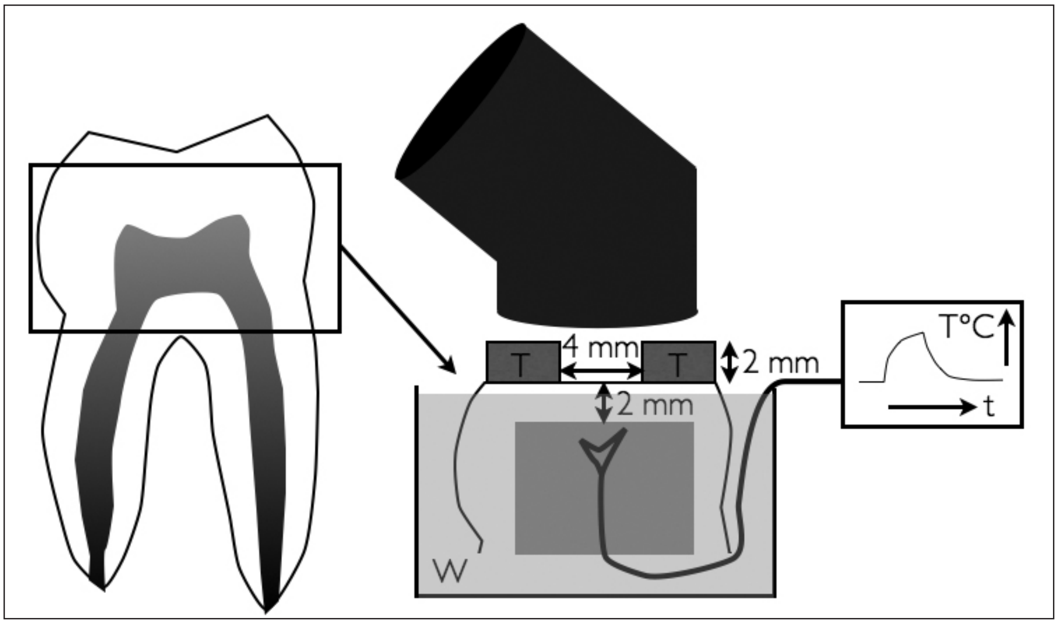

Figure 1. *Experimental setup for the measurement of temperature rise in the pulp chamber; T=Teflon, W=Water, t=time, T°C=Temperature in degrees Celsius.*

Statistical Analysis

A two-way ANOVA ($p<0.05$) was performed to analyze the influence of the light model and irradiation time on the Vickers microhardness at the upper and lower surfaces of the sample. The same test was used to analyze the results of the increase in temperature in the pulp chamber in the three different situations: uncovered tooth, polymerization with 2 mm composite shade A2 and 2 mm Bleach shade.

RESULTS

The absorption spectra of the photoinitiators (pure CQ and L) and emission spectra of the lights (relative intensity) are shown in Figure 2. Based on these results, the LCUs can be divided into three groups: the first group contains the halogen light (X); the second group contains B16i and F2, both of which are second generation LEDs with perfectly overlapping spectra and a peak at 450 nm; the third group contained BG2 and G, which are third-generation LED lights

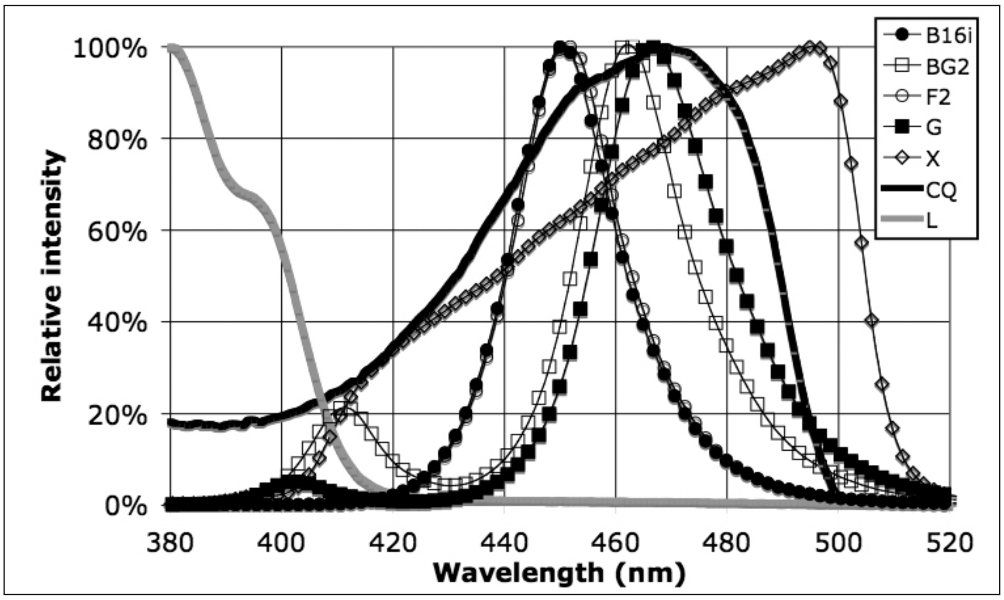

Figure 2. *Absorption spectra of the photoinitiators (pure CQ and L) and emission spectra of the light-curing units (in relative intensity of their respective maximum).*

with a blue peak centered on the maximum absorption peak of CQ—467 nm—and a small violet peak. The comparison between the absorption spectra of the photoinitiators and the emission spectra of the lights (Figure 2) reveals that F2 and B16i should be completely ineffective on L and only effective on CQ. Nevertheless, their emission peak is not centered on the CQ peak of maximum absorption, contrary to G, and to a lesser extent to BG2. B, BG2 and X can excite L, thanks to their emission range below 420 nm. The respective power densities measured by the Bluephase meter are shown in Table 1.

For all ANOVA tests performed, analysis of variance displayed $p<0.001$.

For shade A2 composite, the microhardness values at the upper surface (Figure 3a) were not very discriminant. All irradiation conditions generated VHN values statistically equal to or better than the standard chosen for this study, X–40 seconds. On the lower surface, at 2 mm (Figure 3b), the same observation was made, except for F2–10 seconds for which the VHN was statistically lower than the standard. The VHN values for BG2–40 seconds and B16i–40 seconds at the upper surface were significantly higher than for the standard. At the lower surface, there were more statistical differences, indicating the importance of irradiation time deeper in the material. For example, the results for G–10 seconds, G–20 seconds and G–40 seconds were statistically identical on the upper surface, while they were very different at a depth of 2 mm.

For Bleach shade composite, at the upper surface (Figure 4a), the VHN values for all irradiation times for G and BG2 (10, 20 and 40 seconds) were statistically comparable to the standard, and the VHN values for B16i and F2 were significantly less than the standard. At the lower surface (Figure 4b), the irradiation time was a significant factor, as for shade A2 at this depth. The VHN values for G–10 seconds and BG2–10 seconds were significantly less than for the standard, as were values for F2–10 and 20 seconds.

Figure 5 shows the temperature increase in the pulp chamber (ΔT, in °C) associated with the use of each light for 10, 20 and 40 seconds. In the case of shade A2 (Figure 5a), the three more powerful lights—B16i, BG2 and G—induced higher ΔTs when they were used for 40 seconds. These results were significantly greater than that of X–40 seconds, while BG2 and G used for 20 seconds induced ΔTs that were statistically comparable to that of X–40 seconds. For Bleach shade (Figure 5b), the temperature changes were much lower; only B16i–40 seconds and F2–40 seconds induced a ΔT greater than 4°C. These were followed in decreasing order of ΔT by the same lights for 20 seconds, then by G–40 seconds and BG2–40 seconds. For the uncovered tooth (direct irradiation of the tooth without composite in the mold) (Figure 5c), the results were close to those seen with shade A2 in order, but were about 1°C higher. Thus, comparing Figures 5a, b and c highlights the insulating effect of the resin composite; it also demonstrates the influence of the shade and photoinitiator content on this insulating effect as ΔT values with Bleach shade (Figure 5b) were much lower than those with shade A2 under the same irradiation conditions.

DISCUSSION

First, the authors of the current study will consider the results achieved using the shade A2 composite, which seemed to validate use of the four LED lights for irradiations as short as 10 seconds (except for F2–10 seconds) as an alternative to X–40 seconds, the curing protocol recognized as a reference in the literature.[15-16] Nevertheless, some irradiation conditions generated microhardness that was significantly greater than X–40 seconds—G–40 seconds (lower surface), BG2–40 seconds and B16i–40 seconds (upper/lower surface). This observation is due to the

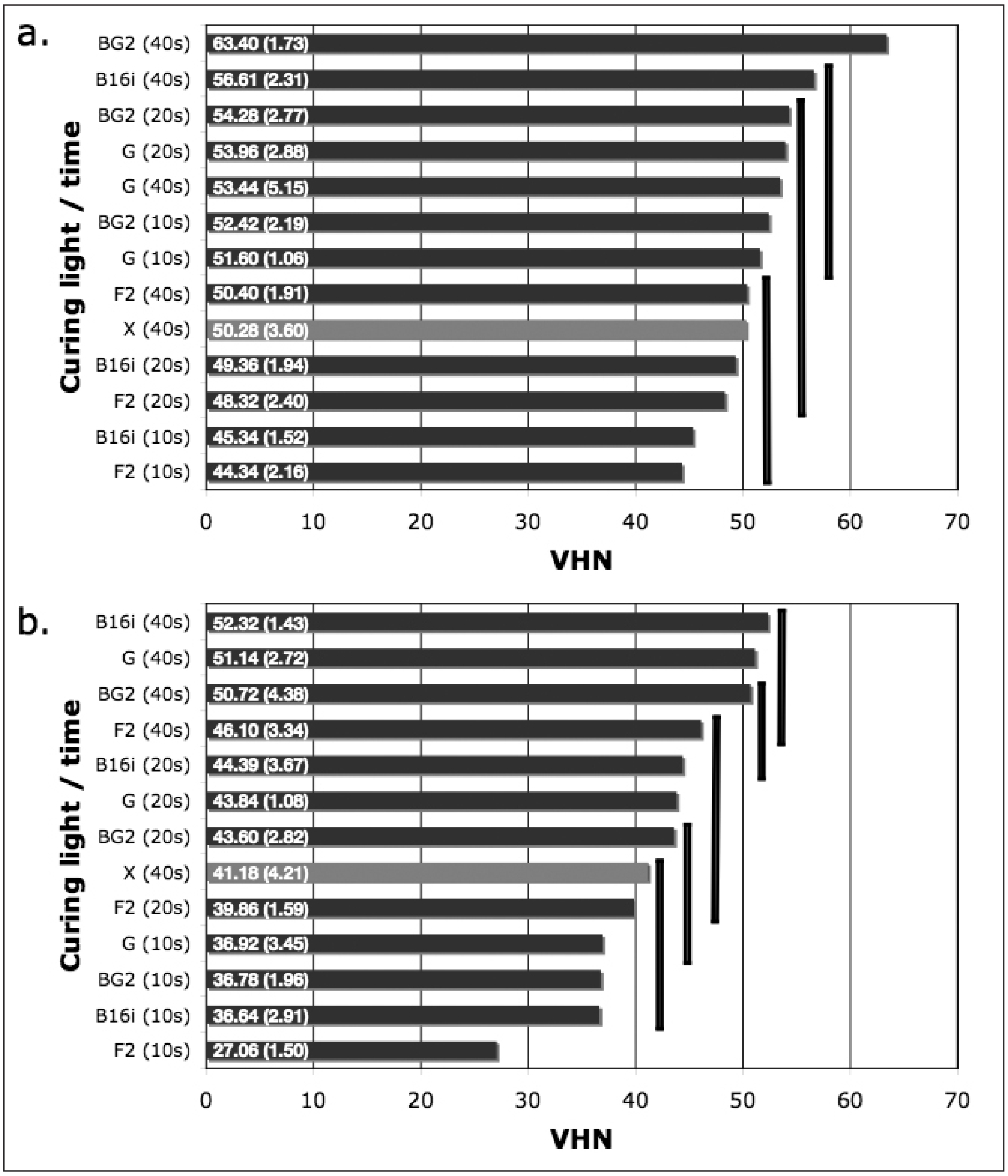

Figure 3. *Vickers microhardness values (VHN) of Tetric Evo Ceram A2 at the upper surface (a) and at 2 mm depth (b) after irradiation with each of the five lights for 10, 20 and 40 seconds. The results for each irradiation condition are ranked in descending order according to their means (n=5); means (+/- standard deviations) and are written in white in each horizontal bar. The horizontal bar corresponding to the reference (XL3000, 40 seconds) is highlighted in light gray. Vertical bars connect materials that are not statistically different (*p*<0.05).*

higher power density of these lights in the area of maximum absorption of CQ.[3] Despite the improvement in microhardness, these irradiation conditions (high-power lights for 40 seconds) can only be validated after consideration of ΔT, which will be discussed below. The comparison between BG2–40 seconds and B16i–40 seconds indicates the importance of having a perfect match between the light spectrum and material spectrum. Despite the much higher power density of B16i compared to BG2, the surface hardness of BG2–40 seconds was greater. This is probably due to better alignment of the BG2 blue peak on the CQ peak of maximum absorption.[15] In addition, the effect of BG2's additional violet peak on the small amount of L in shade A2 composite must certainly not be neglected—these results highlight the potential benefits of a combination of both photoinitiators. On the lower surface at 2 mm, there was greater variability in the results compared to that obtained at the upper surface. Hence, although shorter irradiation times may be sufficient to polymerize composite at the surface, irradiation time is a critical parameter for deeper polymerization. Furthermore, the positive effect of an increase in power density on the degree of conversion seems to be limited. B16i and F2 can reasonably be compared, as their spectra overlap perfectly. On the surface, even though the degree of conversion for B16i–40 seconds was statistically higher than that of F2–40 seconds (56.6 versus 50.4), the difference was not proportional to the huge difference in power density (644 mW/cm^2 for F2 versus 1622 mW/cm^2 for B16i), and at a depth of 2 mm, there was no statistical difference between B16i–40 seconds and F2–40 seconds. According to Dewaele and others,[17] at high levels of power density, an additional increase has limited impact on the degree of conversion. The current results confirm that there is probably an optimum power density for a given composite thickness and irradiation time; above this optimum, any excess can potentially have adverse consequences. Every photon that is absorbed by the

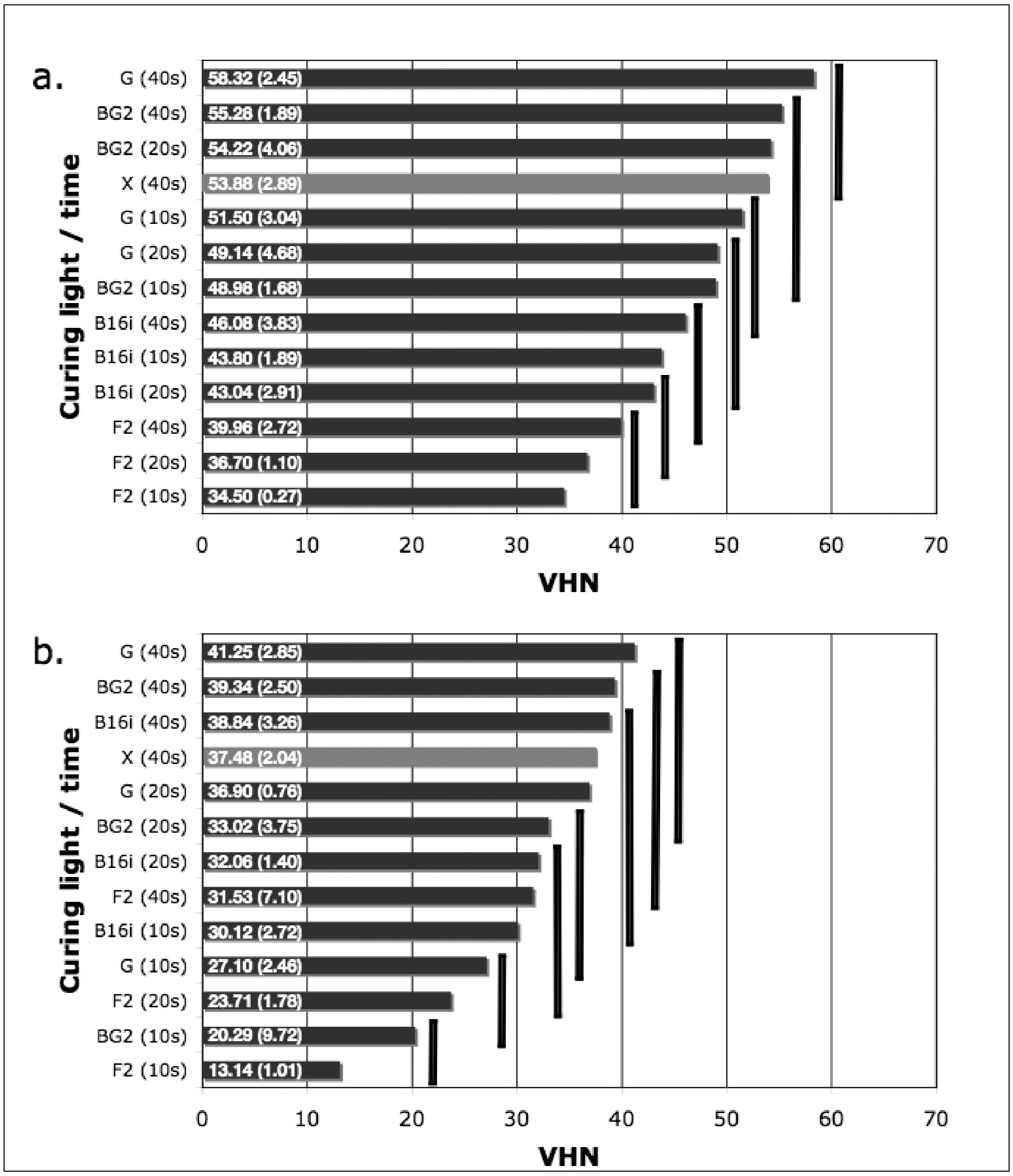

Figure 4. *Vickers microhardness values (VHN) of Tetric Evo Ceram Bleach XL at the top surface (a) and at 2 mm depth (b) after irradiation with each of the five lights for 10, 20 and 40 seconds. The results of each irradiation condition are ranked in descending order according to their means (n=5); means (+/- standard deviations) and are written in white in each horizontal bar. The horizontal bar corresponding to the reference light (XL3000, 40 seconds) is highlighted in light gray. Vertical bars connect materials that are not statistically different (*p*<0.05).*

material heats it, either directly or by the heat of polymerization. As a result, not only should the efficacy in terms of microhardness be considered but also the safety in terms of pulpal heating. This will be addressed later.

The results achieved with the Bleach shade composite will now be discussed. On the surface, LED lights with spectra that were not effective on the main photoinitiator (L)—F2 and B16i—gave statistically lower VHNs than did the standard. In contrast, BG2 and G were even more effective than the standard, regardless of the polymerization time. The high quantum yield efficiency of lucirin accounts for this observation[1] and it enabled good microhardness results despite the lower intensity of the violet peak of BG2 and G compared to the blue peak. The findings were different at the lower surface. B16i–10, 20 and 40 seconds and F2–40 seconds had statistically similar results to that of X–40 seconds, despite the lack of any significant overlap of the spectra of these two lights with lucirin. This is probably an effect of the high molar extinction coefficient of L leading to lower penetration of violet light.[22] In contrast, blue light penetrates deeper into the material due to a lower CQ concentration and molar extinction coefficient. This fact may explain the relatively better efficacy of B16i and F2 on the lower surface compared to the upper one. However, these lights should remain a second choice, and lights that have a spectrum better suited to the absorption spectrum of the material—G and BG2—should be favored. With these two lights (G and BG2), an irradiation time of 20 seconds seems sufficient, as the VHN at 20 seconds was statistically comparable to that at 40 seconds (except for G–40 seconds surface, where a small but significant improvement was observed). Again, ΔT must be considered, which is discussed below.

Finally, when considering microhardness, the current results question a commonly accepted and frequently cited assumption. According to several authors,[7,20,23] an 80% ratio between the hardness of the upper and lower surfaces should be achieved for a satisfactory cure. However, the current results showed significant differences among the hardness values on the upper surface. Hence, analysis of the photopolymerization efficacy based on the upper/lower ratio makes little sense, as both values vary. Indeed, an *inappropriate* curing protocol leading to low absolute conversion values could be validated by a good upper/lower ratio.[15,19] For example, for shade A2 composite, the upper/lower ratios for BG2–40 seconds and X–40 seconds were 80% and 82%, respectively. However, BG2–40 seconds produced significantly better upper (63.4 versus 50.28 for X–40 seconds) and lower (50.72 versus 41.18 for X–40 seconds) microhardness. As the Vickers microhardness is correlated with the degree of conversion,[20-21] the conversion of samples cured with BG2–40 seconds is better than with X–40 seconds, despite their similar and "acceptable" upper/lower ratios.

From the microhardness results, long irradiation times are clearly of interest, as they led to better microhardness on the lower surface. Nevertheless, this positive effect could be partly due to heating the material with light.[15] More importantly, the temperature rise in the pulp chamber followed the same trend. According to the frequently cited study by Zach and Cohen,[24] 5.5°C is the limit above which irreversible pulpal lesions can occur, although this value is controversial. More recent observations contradict the results of Zach and Cohen, most-

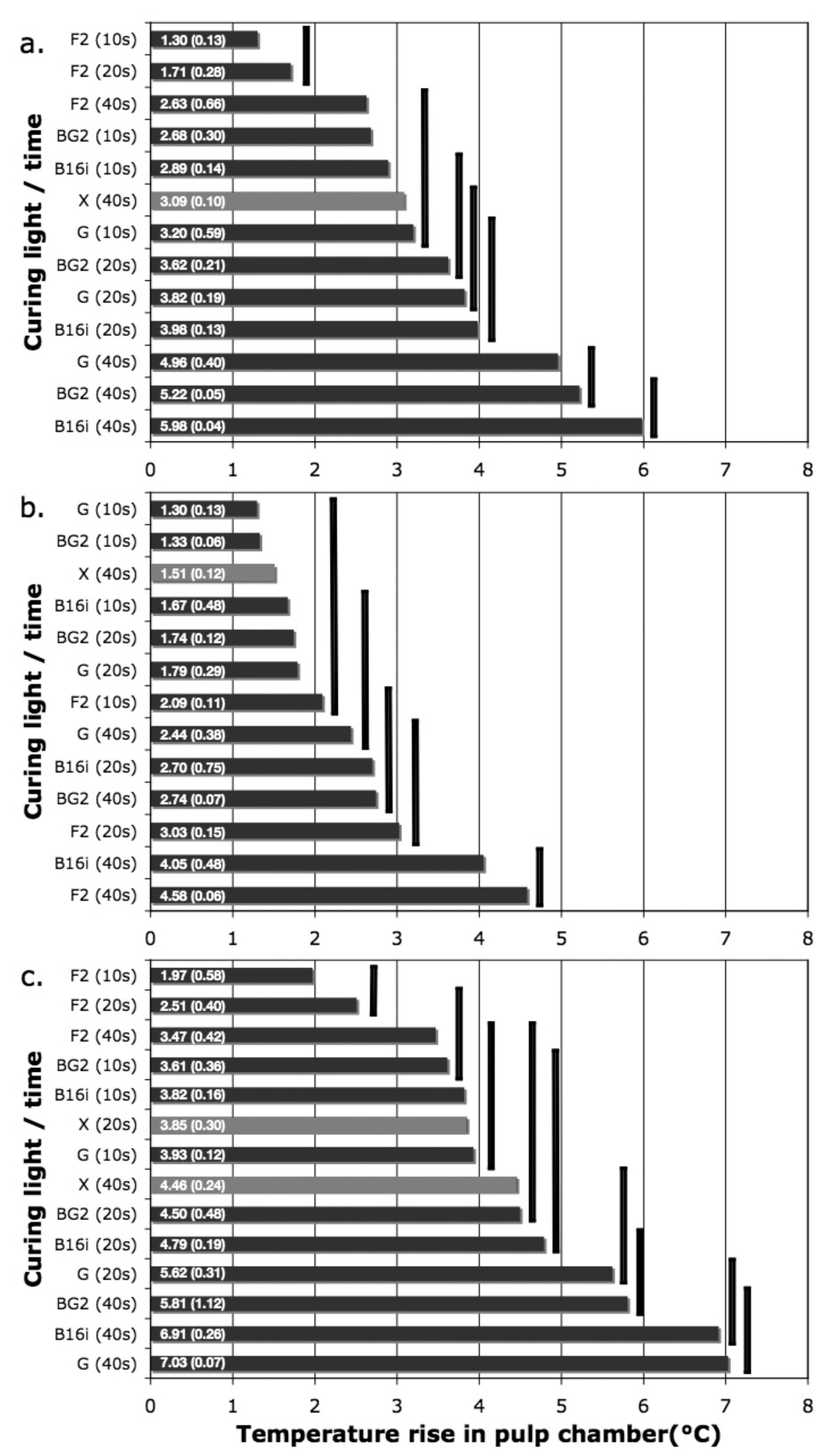

Figure 5. *Increase in pulpal temperature (°C) associated with the use of each light for 10, 20 and 40 seconds when the tooth was covered with 2 mm Tetric Evo Ceram A2 (a) or Bleach XL (b) during thermal measurement or when it was left uncovered (c). The results of each irradiation condition are ranked in ascending order according to their means (n=3); means (+/- standard deviations) and are written in white in each horizontal bar. The horizontal bars corresponding to the reference light (XL3000, 20 seconds–time recommended for polymerization of adhesive–and 40 seconds–time recommended for polymerization of 2 mm composite) are highlighted in light gray. Vertical bars connect materials that are not statistically different* (p<0.05).

ly because the latter results were obtained with prolonged exposition.[25] For example, Baldissara and others[26] reported that short-term exposure to thermal increases ranging from 8.9°C to 14.7°C did not appear to be a major injurious factor for healthy dental pulps. In any case, it seems reasonable to keep pulpal temperature changes as small as possible. Moreover, it is very difficult to predict temperature rise in any particular tooth due to multiple variables, including dentin thickness, preparation depth, output intensity and exposure time.[11] As ΔT is inversely correlated with the remaining dentin thickness,[27] practitioners should be aware that, in the presence of a thinner dentin layer, ΔT values may be higher than those presented in the current study. For example, Tjan and Dunn[28] state that the temperature rise recorded at the light guide tip was reduced by between 8% and 48%, with an interposition of 1 mm dentin and between 40% and 66% with 2 mm dentin. In the current study, the remaining dentin thickness was set to a standard value of 2 mm to focus on the choice of LCU and irradiation time and highlight the trends related to these variables.

In accordance with Jakubinek and others,[25] the current observations indicate that safety criteria need to be determined. Similarly, Schmaltz and Arenholt-Bindslev[29] state that data on thermal effects should be available for all marketed LCUs. As there is no consensus on the critical temperature above which pulpal damage can occur, an improvement in mechanical properties (as a result of an increase in power density and/or time) should only be validated if the associated ΔT is reasonable. Despite the better microhardness values for shade A2 composite obtained with 40-second irradiations with B16i, BG2 and G lights, the ΔT was significantly higher (nearly twice) than the standard (Figure 5a). For these lights, when the irradiation time was reduced to 20 seconds, B16i still induced a significantly higher ΔT than the standard, while for BG2 and G, there were no significant differences in ΔT compared to X–40 seconds. Therefore, for greater safety, BG2 and G should be preferred and used for a maximum of 20 seconds. However, 40 seconds could be recommended in endodontically-treated teeth. For Bleach shade (Figure 5b), the ΔTs were much lower than for shade A2 and, therefore, were less critical in terms of potential pulp damage. For BG2 and G, the LED lights that were most effective in terms of Bleach shade composite microhardness, ΔTs, were lower with 20-second irradiation than with 40 seconds (non-significantly for BG2). As there was no/little improvement in VHN with 40-second irradiation, 20 seconds seems preferable. B16i and F2, whose spectra are not adapted to L, induced the highest ΔTs, close to the 5.5°C threshold, when used for 40 seconds; even with 40 seconds, the highest VHN was significantly less than that of the standard. These lights should, therefore, not be used with Bleach shade composites.

More generally, it seems that composite plays an insulatory role, despite the exothermy of the polymerization reaction.[13,30] This demonstrates that heating induced by light has more impact on temperature rise in the pulp chamber than exothermicity occurring as a result of polymerization of the 2 mm composite. This also confirms that, contrary to what was expected, LEDs have the potential to overheat the pulp. As shown by Asmussen and Peutzfeldt,[10] temperature rise increases with increasing power density. Thus, compared to shade A2 (Figure 5a), Bleach shade (Figure 5b) seems to be more effective at preventing heating of the pulp chamber. This observation can be explained by two phenomena: First, Bleach shade composite microhardness values were somewhat lower than that of shade A2 composite, suggesting a lower degree of conversion, which can explain the lower exothermicity. However, as stated earlier, the impact of this effect is probably minor. Second, Bleach shade composite is very white and probably absorbs less light than the more yellow shades. For this reason, it may be useful to place the extra-white composite as the first layer of the restoration. Note that the thermal values measured here concern the initial and deeper layers of a restoration. Given the insulation effect of the composite, the irradiation time could probably be safely increased for subsequent layers, but this suggestion needs to be verified. Regarding the uncovered tooth (Figure 5c), the results can approximately be assimilated to polymerization of the dental adhesive, as its thin nature would not significantly influence the results.[30] It is obvious that the first restorative step is probably the most critical for the pulp.[13,30] Notably, the most powerful light units, B16i, G and BG2, may represent a risk for the pulp when they are used for 40 seconds or even for 20 seconds. Hence, the irradiation time used for these lights should be carefully adapted for the adhesive layer, with 10 seconds being a safer choice for B16i, BG2 and, especially, for G. In contrast, F2 seems a much safer choice for polymerization of the adhesive layer, as the ΔTs of F2–10 seconds and F2–20 seconds were significantly lower than that of X–20 seconds (the protocol usually advised for the adhesive layer with conventional halogen light). This finding favors use of an LED LCU with a lower power density for polymerization of the adhesive. Of course, the associated adhesion properties also need to be considered, which was not the purpose of the current study.

Finally, even if dentists want to spend as little time as possible per procedure, they need to be wary of the many claims made by LCU manufacturers. The results of the current paper may help clinicians better understand the possible adverse consequences (lack of polymerization and temperature rise in the pulp chamber) of their choice of LCU and/or curing parameters to polymerize materials with different absorption characteristics.

CONCLUSIONS

In summary, the current study provides valuable information on potential problems related to the use of new LED lights to polymerize composites with different photoinitiating systems. First, the authors demonstrated that a perfect correspondence between light and material spectra is of prime concern, both to insure optimal polymerization (assessed by microhardness) and limit heating in the pulp chamber. Manufacturers should, therefore, inform practitioners carefully regarding these spectra. Second, a reduction in curing time is feasible as a result of a better-centered spectrum of LEDs and a higher power density. Nevertheless, despite the limited importance of irradiation time at the surface, time was very important at depth in order to obtain optimum polymerization. Hence, the potential to reduce irradiation time is limited by the need to maintain VHN values as high as possible, especially at depth. In addition, time, and particularly power density, must be optimized to insure reasonable levels of pulpal heating. Notably, practitioners should remember that the effect of an increase in power density on microhardness is limited, and any excess power density can result in unjustified pulp heating in the same way as spectrum mismatch. In conclusion, the best compromise between microhardness and pulp heating must be sought and, in this case, it appears to be achieved with G–20 seconds and BG2–20 seconds. Note that these times are longer than those recommended by the manufacturers; hence, dentists should be aware that the recommended times are probably minimal times and not necessarily optimal times.

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