©Operative Dentistry, 2010, **35-1**, 58-68

Knoop Microhardness Mapping Used to Compare the Efficacy of LED, QTH and PAC Curing Lights

RBT Price • J Fahey • CM Felix

Clinical Relevance

The output of a curing light measured at a distance of 0 mm is a poor indicator of how much light energy will be delivered to a restoration in the mouth. When used for manufacturers' suggested curing times and at clinically relevant distances, some curing lights deliver much less energy than is recommended (<10J/cm^2) and produce softer composites.

SUMMARY

This study used a hardness mapping technique to compare the ability of seven curing lights to polymerize five composites. Six curing lights (Sapphire [plasma-arc: PAC], Bluephase16i [light emitting diode: LED], LEDemetron II [LED], SmartLite IQ [LED], Allegro [LED] and UltraLume-5 [Polywave LED]) were compared to an Optilux 501 (halogen: QTH) light. Five resin composites (Vit-l-escence, Tetric Evoceram, Filtek Z250, 4 Seasons and Solitaire 2) were polymerized at 4 mm and 8 mm from the end of the light guide. Four composites were light cured for the following times using these lights: Sapphire (5 seconds), Bluephase16i (5 seconds), LEDemetron II (5 seconds), SmartLite IQ (10 seconds), UltraLume-5 (10 seconds), Allegro (10 seconds) and Optilux 501 (20 seconds). Solitaire 2 required double these irradiation times. On each specimen, the Knoop microhardness (KHN) was measured at 49 locations across a 3 x 3 mm grid to determine the ability of each light to cure each brand of composite. The PAC light delivered the broadest spectrum of wavelengths, the greatest irradiance and hardness values that were 4.7 to 18.1 KHN_{50gf} harder than the other lights. The ability of the lights to cure these five composites was ranked from highest to lowest: Sapphire, Optilux 501, Allegro, UltraLume-5, SmartLite IQ, LEDemetron II and Bluephase16i (ANOVA with REGWQ multiple comparison adjustment, *p*<0.01).

*Richard BT Price, BDS, DDS, MS, FRCD(c), FDS RCS(Edin), PhD, professor of Prosthodontics, Dalhousie University, Dental Clinical Sciences, Halifax, Nova Scotia, Canada

John Fahey, M Math, biostatistician, Halifax Professional Centre, Halifax, Nova Scotia, Canada

Christopher M Felix, BSc, research assistant, Department of Dental Clinical Sciences, Dalhousie University, Halifax, Nova Scotia, Canada

*Reprint request: 5981 University Avenue, Halifax, Nova Scotia B3H1W2, Canada; e-mail: rbprice@dal.ca

DOI: 10.2341/09-055-L

INTRODUCTION

A basic piece of dental equipment that has made tooth-colored restorations possible is the dental curing light. This light can be a laser, light emitting diode (LED), quartz-tungsten-halogen (QTH) or a plasma arc (PAC) light source. These light-curing units (LCUs) must deliver both sufficient energy and light at the correct wavelengths to produce an acceptably cured restoration.[1-2] The manufacturers of most resin composites recommend that a 2 mm increment of composite should be irradiated for 10 to 40 seconds (see Table 1). However, the manufacturers of the Sapphire (Den-Mat LLC, Santa Maria, CA, USA),[3] LEDemetron II (Kerr Corporation, Orange, CA, USA)[4] and Bluephase 16i (Ivoclar Vivadent Inc, Amherst, NY, USA)[5] advertise that their curing lights can cure composites that are shade A3.5 and lighter in five seconds. The manufacturers of the Optilux 501 (Kerr Corporation),[6] SmartLite IQ (Dentsply International, York, PA, USA)[7] and the Allegro (Den-Mat LLC)[3] advertise an adequate depth of cure when their lights are used for 10 seconds.

Previous research has shown that resin composite at the bottom of deep preparations that finish at or just below the cemento-enamel junction may be 7 mm or more away from the end of the light guide.[8-9] Clinically, this is of concern, because some lights deliver less than 200mW/cm² at a distance of 7 mm from the light guide.[10] Thus, deep restorations (for example, at the gingival areas of an apically extensive proximal box) will receive less than 2 J/cm² when some lights are used for 10 seconds. This is an insufficient amount of energy for adequate polymerization[2,11-12] and may be related to the most common reason why resin composite restorations fail.[13-15] Therefore, the performance of dental curing lights should not be tested at 0 mm from the end of the light guide; instead, they should be tested at more clinically relevant distances. Previous studies have used 4 mm[16] or 5 mm[17] to represent an average distance, and 8 mm[16] or 9 mm to represent an extreme situation.[18-19]

There can be significant differences between light outputs from different examples of the same brand of light,[19-20] but the research literature is replete with studies that test just one example of each curing light. Three examples of each curing light would provide a broader representation of each brand of curing light and facilitate a valid statistical comparison between brands.

The light output from curing lights is rarely a uniform beam, and some lights deliver a greater irradiance at the center of the beam.[17,21] Consequently, more energy is delivered to the center of the specimen, where the resin achieves a greater degree of polymerization.[21] Hardness testing is a reliable and commonly-used method to test how well a resin is cured. The Knoop microhardness test has been shown to be one of the best methods for

Table 1: *Composites, Lot Numbers and Recommended Curing Times*

Resin Composite	Maufacturer	Shade	Lot #	Manufacturer Recommended Curing Times
Tetric EvoCeram	Ivoclar-Vivadent	A2	H30557 H27186 J04088	20 seconds(>550 mW/cm²)
4 Seasons	Ivoclar-Vivadent	A2	H19814 J12132	20 seconds (>500 mW/cm²) 10 seconds (>1200 mW/cm²)
Filtek Z250	3M ESPE	A2	6NW 2TK 6RJ	20 seconds
Vit-l-esence	Ultradent	A2	1T1H B26QW	20 seconds
Solitaire 2	Ultradent Hereaus Kulzer	A2	10248	40 seconds

Table 2: *Curing Lights, Serial Numbers, Light Guides and Curing Times Used*

Curing Light, Light Guide and Type	Maufacturer	Serial #	Curing Times
Sapphire—9 mm (PAC)	Den-Mat	335010037 3395803118 3395802781	5 seconds
Bluephase 16i—8 mm turbo (LED)	Ivoclar-Vivadent	1588078 1588141 1587987	5 seconds
LEDemetron II—8 mm turbo (LED)	Kerr	772010980 782005683 772011773	5 seconds
Allegro—8 mm glass taper (LED)	Den-Mat	44010031 3395900511 339500471	10 seconds
SmartLite IQ 8.5 mm turbo (LED)	Dentsply	100-10951 100-13849 100-95312	10 seconds
UltraLume 5 (LED)	Ultradent	514153 509672 503655	10 seconds
Optilux 501—13 mm standard (QTH)	Kerr	5819102 5814869 58140480	20 seconds

testing the hardness of resin composites, and a good correlation between degree of conversion and the Knoop microhardness has been reported.[22-23] Although a few studies have made multiple hardness measurements on each specimen,[21,24] none have produced detailed hardness maps of the effect of the light on the surface hardness. The majority of previous studies that have evaluated the efficacy of curing lights have taken only a few microhardness readings at the center of the sample, where the specimen may also be the most cured.[25-28] Due to the limited information gathered, these studies are less likely to have produced results that accurately report the amount of polymerization *across* the specimen.

To be clinically relevant for the dentist, the current study tested the ability of seven curing lights to polymerize five composites at distances of 4 mm and 8 mm from the light guide. A mapping technique was used to produce Knoop microhardness maps across a 3 x 3 mm grid on the surface of the composites.

METHODS AND MATERIALS

Five resin composites were cured by seven different dental curing lights (Tables 1 and 2). Five brands of light-emitting diode (LED), one plasma arc (PAC) and one halogen (QTH) light were used. Three examples of each brand of LCU were included. These LCUs and composites were specifically chosen to represent a range of popular products. The lights had a wide range of spectral outputs and the composites used different photoinitiator systems.

The Optilux 501 (QTH) light was used for 20 seconds (or 40 seconds on Solitaire) in the standard curing mode and was designated as the "gold standard" light source. To represent a clinical situation where the end of the light guide is not at 0 mm from the composite, the lights were used at a distance of 4 mm and 8 mm away from the composites.[19-20] Vit-l-escence, Tetric EvoCeram, Filtek Z250 and 4 Seasons resin composites were cured using the following curing times (Table 2): Sapphire (5 seconds), Bluephase16i (5 seconds), LEDemetron II (5 seconds), SmartLite IQ (10 seconds), Allegro (10 seconds) and UltraLume-5 (10 seconds). It was found to be necessary to double these irradiation times for Solitaire 2.

The total light output from each light was recorded using a laboratory grade spectroradiometer (USB 4000, Ocean Optics, Dunedin, FL, USA) and integrating sphere (FOIS-1, Ocean Optics). Where indicated, the batteries in the curing lights were fully charged before use. The irradiance (mW/cm^2) delivered by the lights at 0 mm, 4 mm and 8 mm from the end of the curing lights was recorded using a detector (CC3-UV, Ocean Optics) connected by a fiber optic cable to a USB 4000 spectroradiometer. The irradiance and spectral output of the curing lights were analyzed using SpectraSuite software version 5.1 (Ocean Optics, Dunedin, FL, USA). This system was calibrated using a National Institute of Standards and Technology (NIST, Gaithersburg, MD, USA) referenced light source (Ocean Optics, LS-1-Cal-Int, or the LS-1-CAL). The output from each light was tested three times in a random order of lights and distances. The mean ± standard deviation irradiance values and the total energy densities delivered were calculated.

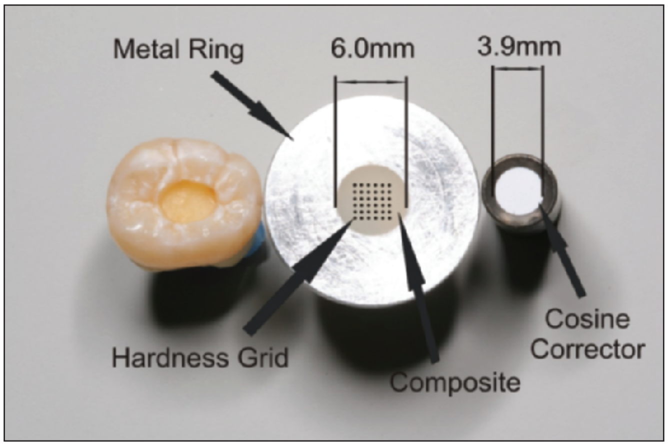


Figure 1: *Size of the light detector in relation to a Class I preparation and the 3 x 3 mm hardness mapping grid.*

The samples of the resin composite were packed into aluminum rings two millimeters thick, with a six-millimeter diameter hole. A thin polyester strip was placed over the top and bottom surfaces, and the composites were light cured for the selected times (Table 2) at a distance of 4 mm or 8 mm. Once cured, the samples were stored at room temperature in the dark for 24 hours. The polyester strips were left on the composites during storage to minimize the formation of an air inhibited layer on the surface of the resins.[29-30] The polyester strips were then removed and 49 Knoop microhardness readings were made on the top and bottom surfaces (Figure 1) using an HM-123 automated hardness tester (Mitutoyo Canada Inc, Mississauga, Ontario, Canada), which applied a 50-gram load for 10 seconds. The hardness tester was preprogrammed to measure Knoop microhardness readings across a 3 x 3 mm grid using a 7 x 7 matrix pattern with a 0.5 mm pitch (Figure 1). The 6 mm diameter hole in the metal ring allowed at least a 1 mm buffer of composite between any hardness measurement and the metal mold. This 1 mm buffer minimized any effect the mold may have had on resin polymerization.[31] The Knoop hardness values (KHN) were exported into a graphing program (SigmaPlot 10, Systat Software, Inc, Point Richmond, CA, USA) to obtain 2D color-coded hardness maps and for statistical analysis. A total of 210 samples were made (5 composites x 7 lights x 3 examples of each light x 2 distances) in a random order of composites and lights. Overall, 588

KHN readings (3 examples of each light x 2 distances x 2 surfaces x 49 readings) were made for each brand of light on each composite and a total of 20,580 KHN readings were taken to compare the ability of the seven curing lights to polymerize the five resin composites.

To be clinically relevant, this study tested the ability of 21 curing lights to cure five brands of resin composite at two distances. This introduced many variables and required an in-depth statistical analysis. First, an analysis of variance (ANOVA) model was fit for hardness, separately for each surface (top and bottom) and for distances of 4 mm and 8 mm. The three different lights of the same model were considered to be a random sample from a population and this random effect was included in the model. Fixed effects for composite, type of light and their interaction were included. Based on the results, a subsequent model was fit, which ignored the random effect, that is, adding its variance to the residual variance. The latter "full" model also included distance and surface (top/bottom) and all possible interactions. A final set of models, fitted separately for each composite, was fit to elucidate the relative hardness provided by different light models, averaging the effect of distance and surface. The analyses were completed using PROC MIXED (for initial random effect model) and PROC GLM statistical procedures[32] in SAS (SAS Institute Inc, Cary, NC, USA) version 9.1.3.

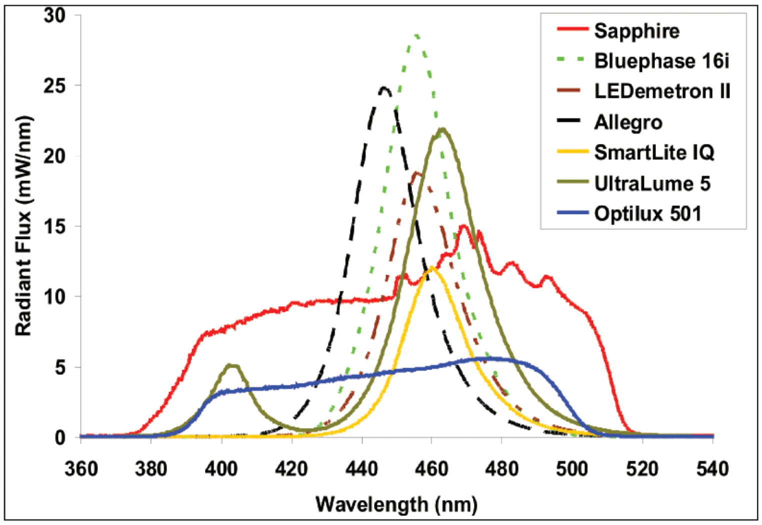


Figure 2: *Spectral output delivered by each light recorded using an integrating sphere attached to an Ocean Optics USB 4000 spectroradiometer.*

Table 3: *Mean Irradiance ± sd and Energy Density From Each LCU Recorded at a Distance of 0 mm, 4 mm and 8 mm From the End of the Light Guide*

0 mm			
Curing Light	**Mean Irradiance (mW/cm²)**	**SD**	**Mean Energy Density (J/cm²)**
Sapphire – (5 seconds)	2693	131	13.5
Bluephase 16i – (5 seconds)	2357	142	11.8
Allegro – (10 seconds)	1650	163	16.5
LEDemetron II – (5 seconds)	1458	132	7.3
UltraLume 5 – (10 seconds)	1357	44	13.6
Optilux 501 – Standard (20 seconds)	1143	240	22.9
SmartLite IQ (10 seconds)	782	165	8.1
4 mm			
Curing Light	**Mean Irradiance (mW/cm²)**	**SD**	**Mean Energy Density (J/cm²)**
Sapphire – (5 seconds)	2636	147	13.2
Allegro – (10 seconds)	1573	53	15.7
Bluephase 16i – (5 seconds)	1231	61	6.2
LEDemetron II – (5 seconds)	1073	68	5.4
Optilux 501 – Standard (20 seconds)	794	170	15.9
SmartLite IQ (10 seconds)	780	121	7.8
UltraLume 5 – (10 seconds)	658	44	6.6
8 mm			
Curing Light	**Mean Irradiance (mW/cm²)**	**SD**	**Mean Energy Density (J/cm²)**
Sapphire – (5 seconds)	2327	107	11.6
Allegro – (10 seconds)	727	77	7.3
Optilux 501 – Standard (20 seconds)	517	93	10.3
SmartLite IQ (10 seconds)	470	47	4.7
Bluephase 16i – (5 seconds)	442	28	2.2
LEDemetron II – (5 seconds)	440	40	2.2
UltraLume 5 – (10 seconds)	325	26	3.2

RESULTS

Figure 2 shows the total spectral output delivered by each light. The spectral output ranged from 375-515 nm. The Sapphire LCU delivered the broadest spectral output and four of the LED lights were conventional single peak LCUs. In contrast, the UltraLume 5 was a dual peak (Third Generation) LED curing light. Table 3 shows the irradiance and energy density delivered by each light at 0 mm, 4 mm and 8 mm to the 3.9 mm diameter detector. At all three distances, the PAC light delivered the

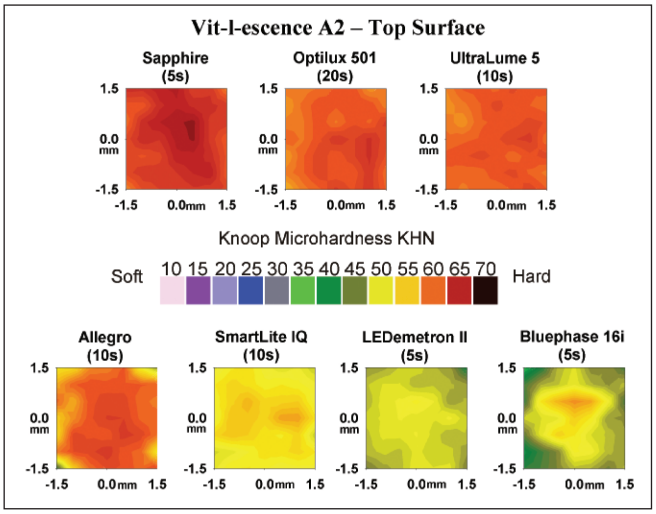


Figure 3: *Surface hardness map across the 3 x 3 mm grid at the top of Vit-l-escence irradiated at a distance of 4 mm.*

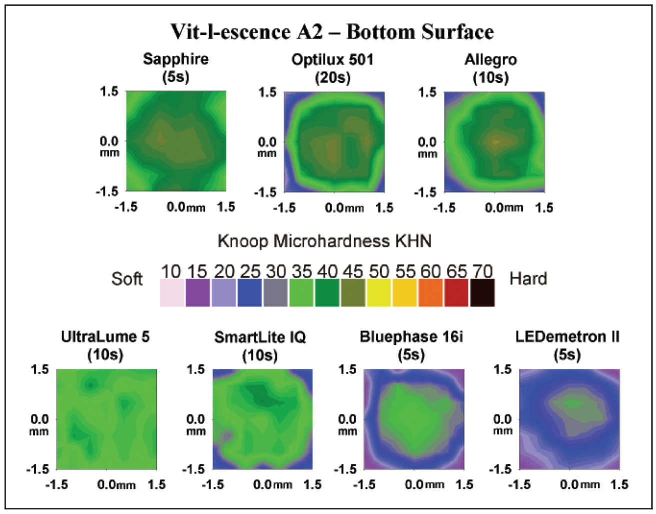


Figure 4: *Surface hardness map across the 3 x 3 mm grid at the bottom of Vit-l-escence irradiated at a distance of 4 mm.*

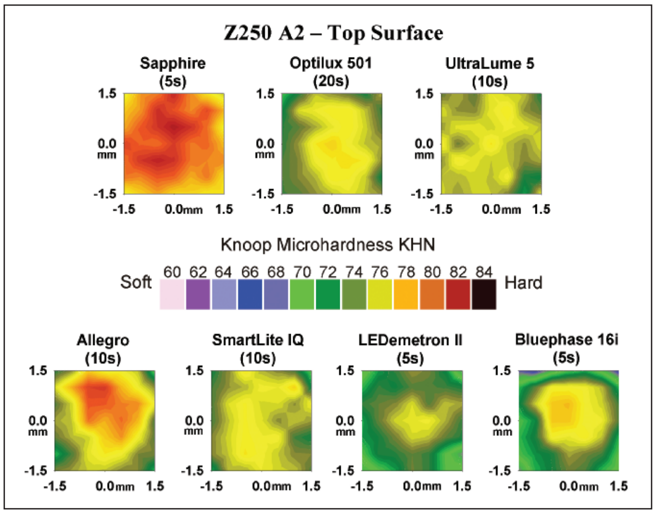


Figure 5: *Surface hardness map across the 3 x 3 mm grid at the top of Filtek Z250 irradiated at a distance of 4 mm.*

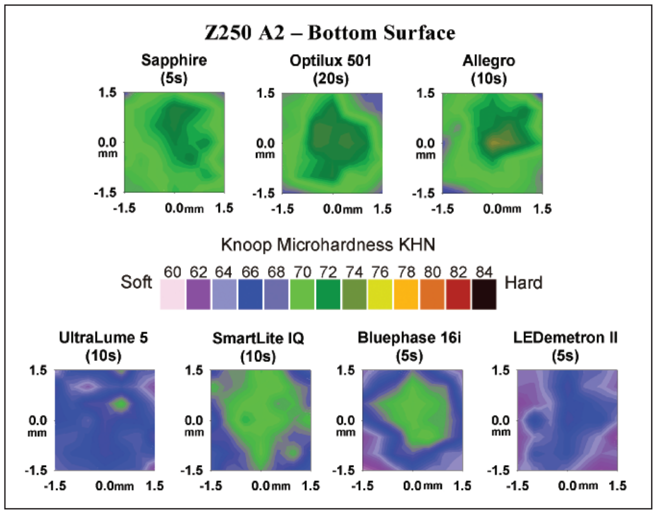


Figure 6: *Surface hardness map across the 3 x 3 mm grid at the bottom of Filtek Z250 irradiated at a distance of 4 mm.*

greatest irradiance (mW/cm^2), but not always the greatest energy density (J/cm^2). Figures 3 through 8 illustrate representative contour maps of the hardness of Vit-l-escence, Z250 and 4 Seasons composites at the top and bottom surfaces cured at a distance of 4 mm. In general, the composites were harder at the center and softer 1.5 mm away from the center.

At the 4 mm distance, the top surface yielded the highest Knoop microhardness values. Overall, Filtek Z250 was the hardest composite and averaged 16.8 KHN_{50gf} harder than Vit-l-essence. Solitaire 2 had the lowest mean hardness, which was 17.1 KHN_{50gf} softer than Vit-l-esence. Overall, when the surface and distance results were combined, the Sapphire LCU produced hardness values that were at least 4.7 KHN_{50gf} higher than any of the other lights and up to 18.1 KHN_{50gf} harder than the light with the lowest values.

The random effect for different lights of the same model had an observed significance level between 1.0% and 1.4% in each of the four ANOVA models (top@4 mm, top@8 mm, bottom@4 mm and bottom@8 mm) for light model and composite. The variance associated with this effect was, in each case, close to an order of magnitude smaller than the residual variance. Since the additional complexity of fitting a model that included a random effect provided little additional benefit, only fixed effects models were further considered. A separate repeated measures ANOVA examined the pattern of hardness results separately across the 3 x 3 mm grid and showed that ranking of the lights was unchanged. Although the extent to which the differences were statistically significant was diminished, they were still significant at the alpha = 1% level.

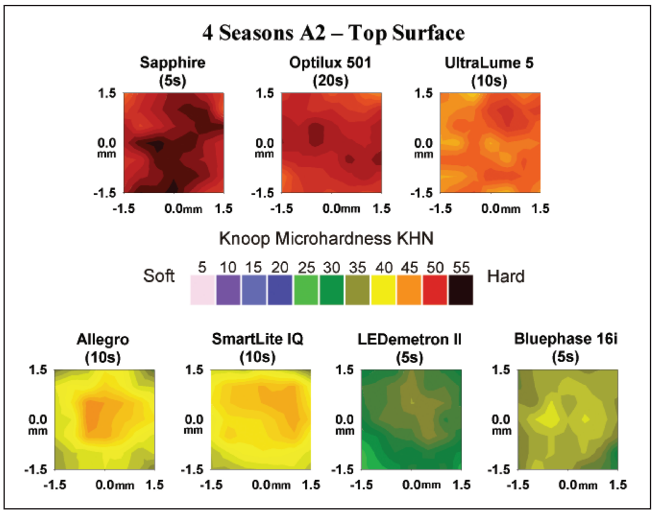


Figure 7: *Surface hardness map across the 3 x 3 mm grid at the top of 4 Seasons irradiated at a distance of 4 mm.*

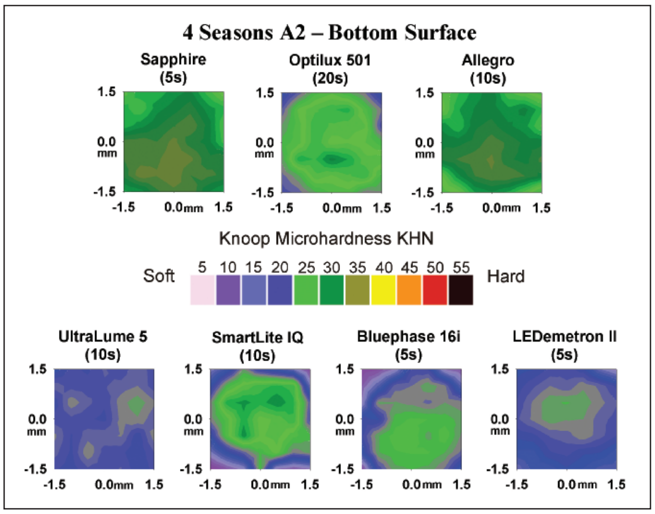
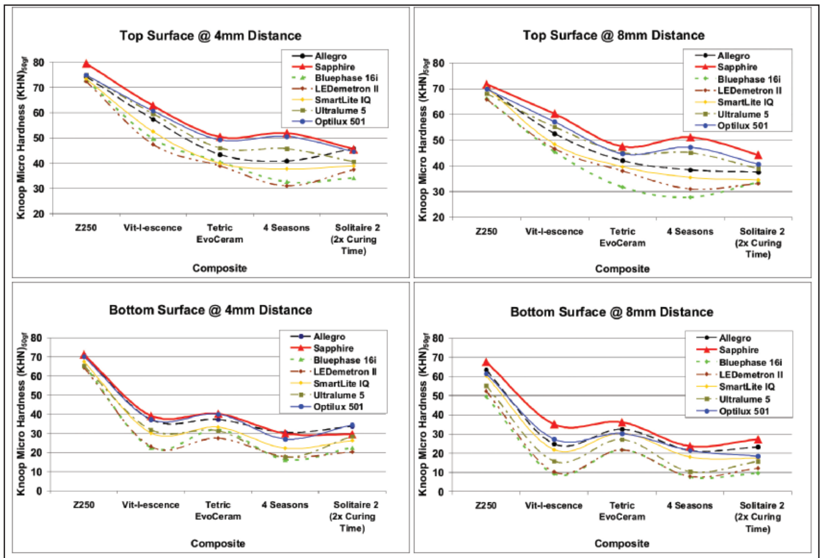


Figure 8: *Surface hardness map across the 3 x 3 mm grid at the bottom of 4 Seasons irradiated at a distance of 4 mm.*

The interaction plots in Figure 9 report the Knoop microhardness values recorded for each composite using each LCU at both distances. These plots illustrate that Filtek Z250 was the hardest composite and show where the interactions occurred between the effects of the light and composite. In general, the Sapphire LCU always produced the hardest and best-cured composites at both distances and at both the top and bottom of the specimens. Hypothesis tests for all main effects and all possible interactions were statistically significant at the 0.0001 level in all models. This reflected the volume of information available.

To control for the unwarranted significance that can be found as a result of performing multiple tests, a standard conservatism adjustment was used. Within each composite, the Type I error rate (that is, mistakenly declaring a statistically significant difference) was controlled using a standard adjustment due to **R**yan-**E**inot-**G**abriel-**W**elsch.[32] Since this was done for each of the five composites, a further conservatism factor was introduced by using an α of 0.01. Figure 10 shows the results of the multiple comparison tests that were used to rank the seven brands of LCUs, separately for each composite. The overall Knoop microhardness produced by each of the seven LCUs on each of the composites was estimated using the SAS GLM procedure.[32] Table 4 shows that the Sapphire LCU consistently produced the hardest composites ($p<0.01$). The rankings of the remaining LCUs were similar, but not identical across the five composites, as illustrated by the interaction plots shown in Figure 9. The results are summarized in Table 5, where the overall performance of the PAC light was compared to all the other lights. In only one of the 20 conditions—the top surface of Solitaire 2 cured at a distance of 4 mm—did the Sapphire LCU not produce the hardest surface ($p>0.01$). Overall, the LCUs were ranked Sapphire (first place), followed by Optilux 501 (using a 20-second cure), Allegro, UltraLume-5, SmartLite IQ, LEDemetron II and Bluephase 16i ($p<0.01$).

To help illustrate the performance of the LCUs, the overall mean KHN values achieved



Curing Times

Sapphire	Bluephase 16i	LEDemetron II	Allegro	SmartLite IQ	UltraLume 5	Optilux 501
5 s	5 s	5 s	10 s	10 s	10 s	20 s

* Curing Time Doubled for Solitaire 2

Figure 9: *Interaction plots showing the average hardness at the top and bottom for every composite cured with every light at both distances. Different Y axis scales used for the Top and Bottom plots to better distinguish the differences.*

by each light were compared, and these overall microhardness values were compared as a percentage of the maximum hardness. The Sapphire LCU produced the greatest hardness values (=100%). The overall hardness values were: Optilux 501–94%, Allegro–91%, UltraLume 5–85%, SmartLite IQ–83%, LEDemetron II–72% and Bluephase 16i–72% of those produced by the Sapphire LCU.

DISCUSSION

Most previous studies that have evaluated the performance of dental curing lights have used a sample size of one light and made multiple measurements using this one light. In an evaluation of 660 curing lights using laboratory grade test equipment, it was reported that the majority of the lights only achieved half of the manufacturer's specified light output.[20] Therefore, to allow for a valid statistical comparison between brands, the current study used three examples of each curing light to provide a representative sample of each curing light. The within-brand effect was measured and, although present, was found to be small when compared to the variability among the four brands of light. As this within-brand variability was not the primary focus of the current study, it was not necessary to test more lights.

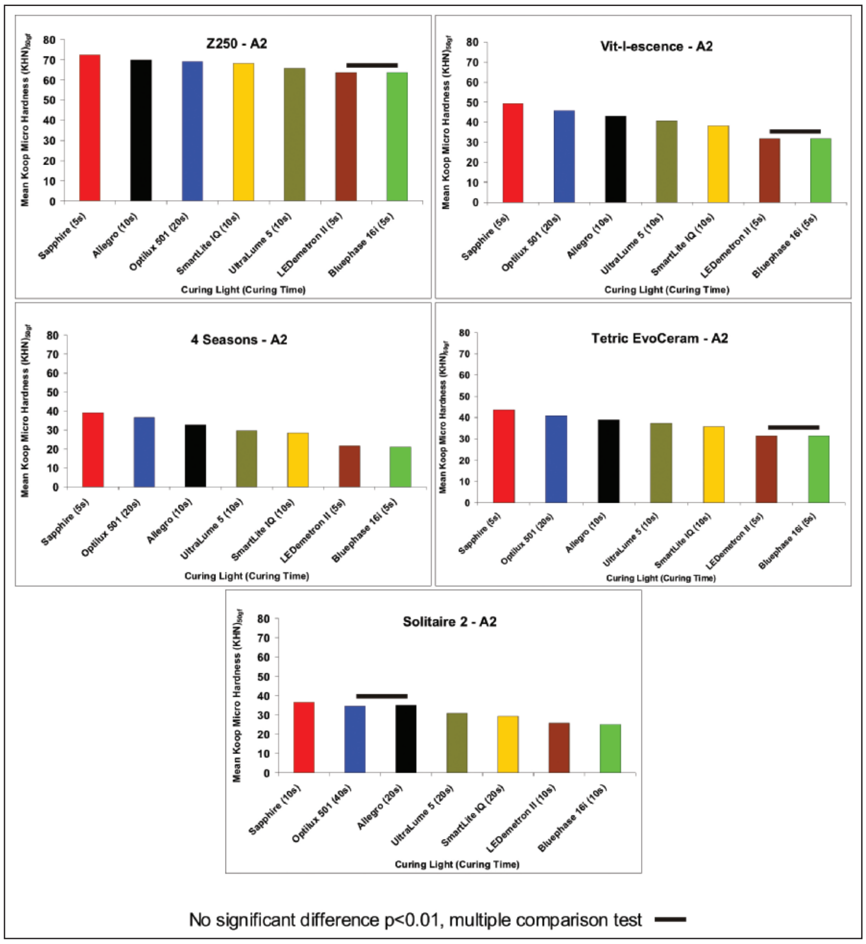


Figure 10: *Effect of the seven LCUs on the overall Knoop microhardness of the five composites. Overall ranking based on the mean microhardness achieved at the top and bottom at both 4 mm and 8 mm distances.*

The manufacturer of the Optilux 501 QTH light claims that this light will cure composites in 10 seconds.[6] It was thought that this QTH curing light, used for double this recommended curing time, would act as the "gold standard" and produce the best cured composites. However, the hardness values produced by this QTH light reached only 94% of those produced by the Sapphire LCU. The expectation that the Optilux 501 high-power halogen curing light used for 20 seconds would produce the best and most-uniformly cured composite at both distances was not substantiated ($p<0.01$).

The results of the current study are clinically relevant, because the major reasons for resin composite restoration failure are secondary caries, restoration fracture and marginal defects.[13-15] These failures may

Table 4: *Overall Ranking of the Performance of Each LCU for Each Composite Based on Hardness at the Top and Bottom and the 4 and 8 mm Distances Combined*

Composite	**4 Seasons**		**Evoceram**		**Solitaire 2**		**Vit-l-escence**		**Z250**		
Curing Light	Group	Mean	Group	Mean	Group	Mean	Group	Mean	Group	Mean	N
Sapphire	**A**	**39.2**	**A**	**43.6**	**A**	**36.7**	**A**	**49.4**	**A**	**72.5**	**588**
Optilux 501	B	36.6	B	41.0	B	34.5	B	45.6	C	69.1	588
Allegro	C	32.8	C	38.8	B	35.1	C	43.0	B	69.7	588
UltraLume-5	D	29.7	D	37.4	C	30.9	D	40.6	E	65.8	588
SmartLite IQ	E	28.4	E	35.8	D	29.2	E	38.3	D	68.1	588
LEDemetron II	F	21.6	F	31.5	E	25.8	F	31.8	F	63.7	588
Bluephase 16i	G	21.1	F	31.5	F	25.0	F	31.7	F	63.6	588

*Statistical differences within each composite determined using the GLM procedure and the **R**yan-**E**inot-**G**abriel-**W**elsch multiple range test (p<0.01). Means with the same letter are not significantly different using REGWQ grouping at α=0.01.*

Table 5: *Overall Performance of the LCUs Compared to the Sapphire LCU on Each Composite and Under Each Condition (surface and distance)*

Distance	Surface	Tetric EvoCeram	4 Seasons	Z250	Vit-l-escence	Solitaire 2
4 mm	Top	=	=	✓	=	x
4 mm	Bottom	=	=	=	=	✓
8 mm	Top	✓	✓	✓	✓	✓
8 mm	Bottom	✓	=	✓	✓	✓

✓ Ranked First
= Ranked Equal First
x Not Ranked First

be due to inadequately curing the resin composite at the margins. This study used the curing light manufacturers' recommended curing times and did not attempt to measure the maximum hardness possible for each composite. These recommendations were probably developed under ideal laboratory settings with the end of the light guide at 90° and 0 mm from the specimen. From this type of bench top research, it is recommended that 2 mm increments of composite should receive between 12 to 36 J/cm^2 of energy to be adequately polymerized.[11-12,33-35] However, Table 3 shows that, at a distance of 8 mm, the Bluephase 16i and LEDemetron II lights delivered only 2.2 J/cm^2 and the SmartLite IQ light delivered 4.7 J/cm^2. This helps to explain why these lights were unable to adequately polymerize the resins. In contrast, the Sapphire LCU light delivered a greater energy density (11.6 J/cm^2), which, together with its broad spectral output, explains why this light produced the hardest composites. To deliver 20 J/cm^2 of energy to deep preparations, the curing time would have to be extended to 45 seconds when the BluePhase 16i and the LEDemetron II lights are used. Thus, as the distance from the light increases, the shortened curing times suggested by some manufacturers may result in an inadequately cured composite. This has many undesirable consequences, including reduced physical properties,[36] reduced bond strengths,[37-38] increased wear,[39] breakdown at the margins of the restoration[40] and decreased biocompatibility.[41-43]

Many previous studies that have evaluated the performance of curing lights have measured the output using simple dental radiometers and have assumed that the output measured at the end of the light guide was the irradiance received by the specimens.[28,44-45] Dental radiometers are not as accurate as laboratory grade power meters and do not report the irradiance actually received by the resin specimen.[46-47] The light detector used in the current study was located in the same position as the resin. Figure 1 shows that the 3.9 mm diameter detector was similar in diameter to both that of a Class I preparation in a tooth and the 3 x 3 mm size of the hardness maps used in the current study. Thus, Table 3 is an accurate report of how much light the resin composites actually received.

Although Figures 9 and 10 show that the Knoop microhardness values were significantly different among the five composites ($p<0.01$), this does not mean that one composite was better cured than another, only that there was a difference in hardness among the five brands of composite. The authors of the current study chose to test shade A2 resin composites, since this is a popular shade that has been used in previous studies.[24,48] It has also been reported that the colorants in shade A2 have the least effect on resin polymerization.[49] Solitaire 2 was used in the current study, because it was known to be difficult to cure.[50] When Solitaire 2 received the same total energy as the other composites, the bottom surfaces of the specimens irradiated at a distance of 8 mm were not hard enough to be measured using the 50 gram load on the Knoop hardness indenter. Consequently, the irradiation times had to be increased. However, even when Solitaire 2 received double the irradiation time and energy density, especially at the 8 mm distance, the bottom surface of Solitaire 2 proved difficult to cure compared to the other composites.

The current study used the light guides that were supplied with the curing lights. Table 3 shows that the effect of the distance from the end of some light guides on irradiance received is different for each light. The Bluephase 16i and LEDemetron II lights used "turbo" light guides, and the results shown in Table 3 support previous studies showing that there is a rapid decrease in irradiance as distance increases from "turbo" light guides.[9-10,17,21,51] This had a significant negative effect on the energy density delivered to the composites and explains why these LCUs did not cure the composites very well at the 8 mm distance. Conversely, light output from the Sapphire LCU was well collimated and did not disperse as rapidly as that from the other light guides. Thus, the Sapphire LCU produced the hardest, most cured composites at both 4 mm and 8 mm from the end of the light guide. Although the SmartLite IQ delivered a relatively low irradiance at 0 mm, this LCU maintains its light output as the distance increases.[17] Tables 3 and 4 show that, at a distance of 8 mm, the SmartLite IQ used for 10 seconds delivered 4.7 J/cm^2 and outperformed the LEDemetron II and Bluephase 16i lights when they were used for five seconds.

The hardness maps (Figures 3-8) illustrate that the hardness is not uniform across the surface of the restoration. These maps highlight differences between the hardness at the top and bottom surfaces. These maps also show that the hardness values were often greater at the center of the specimens. This supports previous studies showing that the light output at the end of the curing lights is not always uniform.[17,21] Most previous studies that have evaluated the efficacy of curing lights have only taken a few microhardness readings in the center of the sample.[25-28] Figures 3 through 8 show why previous studies probably produced results that do not accurately represent the ability of the LCU to cure the entire specimen.

In recent years, light-emitting diodes have been used to create compact, cordless LCUs. However, as shown in Figure 2, most LED curing lights produce a very narrow spectrum of light compared to either QTH or PAC lights that deliver a broader spectrum of light (from ~375 to 515nm). Some bonding systems and resin composites do not use camphorquinone as the photoinitiator. Instead, they use other photoinitiating components ("alternative initiators"), such as monoacylphosphine oxide (Lucirin TPO)[52] or 1-Phenyl 1,2-Propanedione (PPD),[26,53] which are more sensitive to the wavelengths of light <410 nm and less sensitive to blue light in the 450-480 nm range.[44,54] These resins should benefit from the additional wavelengths provided by the polywave LED or the broader spectrum PAC and QTH lights.[17,24-25,44,55] For example, Figure 2 shows that the Sapphire LCU has a broader spectral output compared to the Allegro LCU. Although Allegro delivered 15.7 J/cm^2 at 4 mm, this light was outperformed by the Sapphire light, even though it delivered a lower total energy (13.2 J/cm^2). The UltraLume 5 is a polywave LED curing light and delivers a broader spectral output compared to the Allegro, LEDemetron II and Bluephase 16i lights, but Table 3 shows that the total energy delivered by the UltraLume 5 light in 10 seconds was low (6.6 J/cm^2 at 4 mm and 3.2 J/cm^2 at 8 mm). Thus, to be effective, a curing light must deliver both a broad spectral output and sufficient energy at clinically relevant distances.

Although the current study tested five brands of resin composite, there are many more resins and shades available on the market. Future studies will include lighter bleaching or translucent shades, since they may produce different results.[1,16,56] To be prudent, dentists should always check that the curing light used for their curing times and at clinically relevant distances cures the bottom of the particular brand and shades of resin composite that they use in their practice. Curing test rings (for example, #043952114, Den-Mat) are available and provide the dentist with a simple method to determine if the light cures the top and bottom surfaces of composites.

CONCLUSIONS

When the seven LCUs used in the current study were used to cure Vit-l-escence, Tetric EvoCeram, Z250 and 4 Seasons for the following curing times: Sapphire (5 seconds), Bluephase16i (5 seconds), LEDemetron II (5 seconds), SmartLite IQ (10 seconds), UltraLume-5 (10 seconds), Allegro (10 seconds), Optilux 501 (20 seconds) and Solitaire 2 for double these curing times, multiple comparison tests from the GLM showed that the effects of light, composite, surface, distance and all their interactions, were significant (p<0.01).

1. For the five composites tested, the Sapphire LCU produced the hardest composites at both 4 mm and 8 mm from the end of the light guide (p<0.01). This LCU also delivered the broadest spectrum of wavelengths and the greatest irradiance at 0 mm, 4 mm and 8 mm from the end of the light guide.
2. The Sapphire LCU delivered hardness values that were between 4.7 and 18.1 KHN_{50gf} harder than the other lights. Based on the overall hardness values, the lights were ranked Sapphire (first place), followed by Optilux 501, Allegro, UltraLume-5, SmartLite IQ, LEDemetron II and Bluephase 16i (p<0.01).
3. The Knoop microhardness values were significantly different among the five composites (p<0.01). Filtek Z250 composite produced the hardest surfaces, which were, on average, 33.9 KNH_{50gf} harder than Solitaire 2.

Acknowledgements

This study was supported by Dalhousie University a NSERC Discovery Grant #298326, and an unrestricted research grant from Den-Mat, Santa Maria, CA, USA.

(Received 17 February 2009)

References

1. Price RB & Felix CA (2009) Effect of delivering light in specific narrow bandwidths from 394 to 515nm on the microhardness of resin composites *Dental Materials* **25(7)** 899-908.
2. Nomoto R (1997) Effect of light wavelength on polymerization of light-cured resins *Dental Materials Journal* **16(1)** 60-73.
3. Den-Mat Sapphire Curing Light Instructions (2007) Den-Mat Corp, Santa Maria, CA.
4. Kerr LEDemetron II Curing Light Instructions (2007) Kerr Corp, Orange, CA.
5. Ivoclar-Vivadent Bluephase 16i Curing Light Instructions (2007) Ivoclar-Vivadent, Amherst, NY.

6. Kerr Optilux 501 Curing Light Instructions (2007) Kerr Corp, Orange, CA.
7. Dentsply SmartLite IQ Curing Light Instructions (2007) Dentsply, York, PA.
8. Yearn JA (1985) Factors affecting cure of visible light activated composites *International Dental Journal* **35(3)** 218-225.
9. Price RB, Dérand T, Sedarous M, Andreou P & Loney RW (2000) Effect of distance on the power density from two light guides *Journal of Esthetic Dentistry* **12(6)** 320-327.
10. Felix CA & Price RB (2003) The effect of distance from light source on light intensity from curing lights *Journal of Adhesive Dentistry* **5(4)** 283-291.
11. Calheiros FC, Daronch M, Rueggeberg FA & Braga RR (2008) Degree of conversion and mechanical properties of a BisGMA:TEGDMA composite as a function of the applied radiant exposure *Journal of Biomedical Materials Research B Applied Biomaterials* **84(2)** 503-509.
12. Lovell LG, Newman SM, Donaldson MM & Bowman CN (2003) The effect of light intensity on double bond conversion and flexural strength of a model, unfilled dental resin *Dental Materials* **19(6)** 458-465.
13. Brunthaler A, Konig F, Lucas T, Sperr W & Schedle A (2003) Longevity of direct resin composite restorations in posterior teeth *Clinical Oral Investigations* **7(2)** 63-70.
14. Opdam NJ, Bronkhorst EM, Roeters JM & Loomans BA (2007) A retrospective clinical study on longevity of posterior composite and amalgam restorations *Dental Materials* **23(1)** 2-8.
15. Bernardo M, Luis H, Martin MD, Leroux BG, Rue T, Leitao J & DeRouen TA (2007) Survival and reasons for failure of amalgam versus composite posterior restorations placed in a randomized clinical trial *Journal of the American Dental Association* **138(6)** 775-783.
16. Bennett AW & Watts DC (2004) Performance of two blue light-emitting-diode dental light curing units with distance and irradiation-time *Dental Materials* **20(1)** 72-79.
17. Vandewalle KS, Roberts HW, Andrus JL & Dunn WJ (2005) Effect of light dispersion of LED curing lights on resin composite polymerization *Journal of Esthetic Restorative Dentistry* **17(4)** 244-254; discussion 254-245.
18. Price RB, Ehrnford L, Andreou P & Felix CA (2003) Comparison of quartz-tungsten-halogen, light-emitting diode, and plasma arc curing lights *Journal of Adhesive Dentistry* **5(3)** 193-207.
19. Price RB, Felix CA & Andreou P (2003) Evaluation of a second-generation LED curing light *Journal of the Canadian Dental Association* **69(10)** 666.
20. Ernst CP, Busemann I, Kern T & Willershausen B (2006) [Feldtest zur Lichtemissionsleistung von Polymerisationsgeräten in zahnärztlichen Praxen] *Deutsche Zahnärztliche Zeitschrift* **61(9)** 466-471.
21. Vandewalle KS, Roberts HW & Rueggeberg FA (2008) Power distribution across the face of different light guides and its effect on composite surface microhardness *Journal of Esthetic Restorative Dentistry* **20(2)** 108-117; discussion 118.
22. Ferracane JL (1985) Correlation between hardness and degree of conversion during the setting reaction of unfilled dental restorative resins *Dental Materials* **1(1)** 11-14.
23. Rueggeberg FA & Craig RG (1988) Correlation of parameters used to estimate monomer conversion in a light-cured composite *Journal of Dental Research* **67(6)** 932-937.
24. Price RB, Felix CA & Andreou P (2006) Third-generation vs a second-generation LED curing light: Effect on Knoop microhardness *Compendium of Continuing Education Dentistry* **27(9)** 490-496; quiz 497, 518.
25. Uhl A, Mills RW & Jandt KD (2003) Photoinitiator dependent composite depth of cure and Knoop hardness with halogen and LED light curing units *Biomaterials* **24(10)** 1787-1795.
26. Schneider LF, Pfeifer CS, Consani S, Prahl SA & Ferracane JL (2008) Influence of photoinitiator type on the rate of polymerization, degree of conversion, hardness and yellowing of dental resin composites *Dental Materials* **24(9)** 1169-1177.
27. Torno V, Soares P, Martin JM, Mazur RF, Souza EM & Vieira S (2008) Effects of irradiance, wavelength, and thermal emission of different light curing units on the Knoop and Vickers hardness of a composite resin *Journal of Biomedical Materials Research B Applied Biomaterials* **85(1)** 166-171.
28. Mobarak E, Elsayad I, Ibrahim M & El-Badrawy W (2009) Effect of LED light-curing on the relative hardness of tooth-colored restorative materials *Operative Dentistry* **34(1)** 65-71.
29. Gauthier MA, Stangel I, Ellis TH & Zhu XX (2005) Oxygen inhibition in dental resins *Journal of Dental Research* **84(8)** 725-729.
30. Park SH, Krejci I & Lutz F (2000) Hardness of celluloid strip-finished or polished composite surfaces with time *Journal of Prosthetic Dentistry* **83(6)** 660-663.
31. Harrington E & Wilson HJ (1993) Depth of cure of radiation-activated materials-effect of mould material and cavity size *Journal of Dentistry* **21(5)** 305-311.
32. Welsch RE (1977) Stepwise multiple comparison procedures *Journal of the American Statistical Association* **72(359)** 566-575.
33. Lee SY & Greener EH (1994) Effect of excitation energy on dentine bond strength and composite properties *Journal of Dentistry* **22(3)** 175-181.
34. Ivoclar-Vivadent (2008) Tetric Evoceram: Instructions for Use Ivoclar Vivadent AG, Schaan/Liechtenstein.
35. Calheiros FC, Kawano Y, Stansbury JW & Braga RR (2006) Influence of radiant exposure on contraction stress, degree of conversion and mechanical properties of resin composites *Dental Materials* **22(9)** 799-803.
36. Lohbauer U, Rahiotis C, Kramer N, Petschelt A & Eliades G (2005) The effect of different light-curing units on fatigue behavior and degree of conversion of a resin composite *Dental Materials* **21(7)** 608-615.
37. Kim SY, Lee IB, Cho BH, Son HH & Um CM (2006) Curing effectiveness of a light emitting diode on dentin bonding agents *Journal of Biomedical Materials Research B Applied Biomaterials* **77(1)** 164-170.

38. Staudt CB, Krejci I & Mavropoulos A (2006) Bracket bond strength dependence on light power density *Journal of Dentistry* **34(7)** 498-502.

39. Condon JR & Ferracane JL (1997) *In vitro* wear of composite with varied cure, filler level, and filler treatment *Journal of Dental Research* **76(7)** 1405-1411.

40. Vandewalle KS, Ferracane JL, Hilton TJ, Erickson RL & Sakaguchi RL (2004) Effect of energy density on properties and marginal integrity of posterior resin composite restorations *Dental Materials* **20(1)** 96-106.

41. Moin Jan C, Nomura Y, Urabe H, Okazaki M & Shintani H (2001) The relationship between leachability of polymerization initiator and degree of conversion of visible light-cured resin *Journal of Biomedical Materials Research* **58(1)** 42-46.

42. Franz A, Konig F, Anglmayer M, Rausch-Fan X, Gille G, Rausch WD Lucas T, Sperr W & Schedle A (2003) Cytotoxic effects of packable and nonpackable dental composites *Dental Materials* **19(5)** 382-392.

43. Knezevic A, Zeljezic D, Kopjar N & Tarle Z (2008) Cytotoxicity of composite materials polymerized with LED curing units *Operative Dentistry* **33(1)** 23-30.

44. Ye Q, Wang Y, Williams K & Spencer P (2007) Characterization of photopolymerization of dentin adhesives as a function of light source and irradiance *Journal of Biomedical Materials Research B Applied Biomaterials* **80(2)** 440-446.

45. Hasler C, Zimmerli B & Lussi A (2006) Curing capability of halogen and LED light curing units in deep Class II cavities in extracted human molars *Operative Dentistry* **31(3)** 354-363.

46. Roberts HW, Vandewalle KS, Berzins DW & Charlton DG (2006) Accuracy of LED and halogen radiometers using different light sources *Journal of Esthetic Restorative Dentistry* **18(4)** 214-222; discussion 223-214.

47. Leonard DL, Charlton DG & Hilton TJ (1999) Effect of curing-tip diameter on the accuracy of dental radiometers *Operative Dentistry* **24(1)** 31-37.

48. Soh MS, Yap AU & Siow KS (2003) Effectiveness of composite cure associated with different curing modes of LED lights *Operative Dentistry* **28(4)** 371-377.

49. Bayne SC, Heymann HO & Swift EJ Jr (1994) Update on dental composite restorations *Journal of the American Dental Association* **125(6)** 687-701.

50. Herrero AA, Yaman P & Dennison JB (2005) Polymerization shrinkage and depth of cure of packable composites *Quintessence International* **36(1)** 25-31.

51. Corciolani G, Vichi A, Davidson CL & Ferrari M (2008) The influence of tip geometry and distance on light-curing efficacy *Operative Dentistry* **33(3)** 325-331.

52. Palin WM, Senyilmaz DP, Marquis PM & Shortall AC (2008) Cure width potential for MOD resin composite molar restorations *Dental Materials* **24(8)** 1083-1094.

53. Ogunyinka A, Palin WM, Shortall AC & Marquis PM (2007) Photoinitiation chemistry affects light transmission and degree of conversion of curing experimental dental resin composites *Dental Materials* **23(7)** 807-813.

54. Park YJ, Chae KH & Rawls HR (1999) Development of a new photoinitiation system for dental light-cure composite resins *Dental Materials* **15(2)** 120-127.

55. Martinelli J, Pires-de-Souza Fde C, Casemiro LA, Tirapelli C & Panzer H (2006) Abrasion resistance of composites polymerized by light-emitting diodes (LED) and halogen light-curing units *Brazilian Dental Journal* **17(1)** 29-33.

56. Alvim HH, Alecio AC, Vasconcellos WA, Furlan M, de Oliveira JE & Saad JR (2007) Analysis of camphorquinone in composite resins as a function of shade *Dental Materials* **23(10)** 1245-1249.