Applied

RESEARCH

Effect of Reduced Exposure Times on the Microhardness of 10 Resin Composites Cured by High-Power LED and QTH Curing Lights

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ABSTRACT

Purpose: To compare the effect of reduced exposure times on the microhardness of resin composites cured with a "second-generation" light-emitting diode (LED) curing light and a quartz—tungsten–halogen (QTH) curing light.

Methods: Ten composites were cured with a LED curing light for 50% of the manufacturers' recommended exposure time or a QTH light at the high power setting for 50% of the recommended time or on the medium power setting for 100% of the recommended time. The composites were packed into Class I preparations in extracted human molar teeth and cured at distances of 2 or 9 mm from the light guide. The moulds were separated, and the Knoop microhardness of the composites was measured down to 3.5 mm from the surface.

Results: The LED light delivered the greatest irradiance at 0 and 2 mm, whereas the QTH light on the standard (high power) setting delivered the highest irradiance at 9 mm. According to distribution-free multiple comparisons of the hardness values, at 2 mm from the light guide the LED light (50% exposure time) was ranked better than or equivalent to the QTH light on the high power setting (50% exposure time) or on the medium power setting (100% exposure time). At 9 mm, the LED light was ranked better than or equivalent to the QTH light (both settings) to a depth of 1.5 mm, beyond which composites irradiated by the LED light were softer ($p < 0.01$). At both distances, the QTH light operated on the high power setting for 50% of the recommended exposure time produced composites that were as hard as when they were exposed on the medium power setting for 100% of the recommended exposure time.

Conclusions: The ability to reduce exposure times with high-power LED or QTH lights may improve clinical time management.

MeSH Key Words: composite resins/chemistry; hardness; light; materials testing/instrumentation

© _J Can Dent Assoc_ 2006; 72(3):147
This article has been peer reviewed.

Curing lights that use light-emitting diodes (LEDs) are becoming increasingly popular in dental practice. Compared with conventional quartz–tungsten–halogen (QTH) curing lights, LEDs convert electronic energy into light energy more efficiently and produce less heat, and many LED curing lights are battery-powered. In addition, LEDs are rugged and can last for thousands of hours,[1] in contrast to the 30- to 50-hour lifespan of conventional QTH bulbs, which are fragile and costly to replace.[2]

To date, there is no internationally accepted classification of the various types of LED curing lights. Most of the initial or "first-generation" LED curing lights were unable to cure composites as well as correctly functioning QTH lights.[3–7] However, LED technology has

Table 1 Composites tested and manufacturers' recommended exposure times

Resin composite and shade	Manufacturer	Recommended exposure time (s)
Z250	3M ESPE, St. Paul, Minn.	
Shade A2		20
Shade B0.5		30
Supreme	3M ESPE, St. Paul, Minn.	
Shade A2D		40
Shade A2B		20
Esthet-X	Dentsply, Milford, Del.	
Shade A2B		20
Shade A2O		20
Heliomolar	Ivoclar-Vivadent AG, Schaan, Liechtenstein	
Shade A2		40
Shade 110T		40
Tetric Ceram	Ivoclar-Vivadent AG, Schaan, Liechtenstein	
Shade A2		40
Bleach XL		40

advanced, and it has been reported that high-power "second-generation" LED curing lights can polymerize some resins as well as or better than some QTH lights.[2,3,5,8–11] The FreeLight 2 curing light (3M ESPE, St. Paul, Minn.) uses one second-generation high-power LED. This light delivers a greater power and irradiance than first-generation models (e.g., the original FreeLight, 3M ESPE), many of which required multiple LEDs to produce an acceptable light output.

If a resin composite restoration does not receive sufficient light exposure at the correct wavelengths, the degree of polymerization is inadequate.[12–14] Previous studies have reported that a QTH light should deliver a minimum irradiance (power density) of 300 to 400 mW/cm^2 to adequately cure a 1.5- to 2-mm increment of resin composite.[14–16] Although many curing lights can produce much more than 400 mW/cm^2, the spectral emission from some of these curing lights may not match the absorption characteristics of the photosensitizers used in the resin composites, which then fail to polymerize adequately despite receiving sufficient total light energy.[2–7,9,10,17,18]

Because many of the newer LED lights deliver more than 400 mW/cm^2, it may be possible to reduce the exposure time from that recommended by composite manufacturers. The hypothesis for this study was that a high-power LED or QTH curing light operated for half the recommended exposure time would yield comparable or greater microhardness numbers for a range of resin composites than a medium-power QTH curing light operated for the full recommended exposure time.

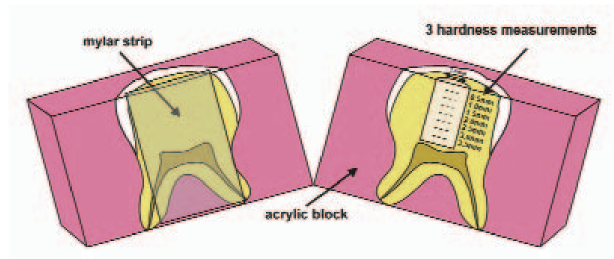

Figure 1: Class I preparation in a tooth mould filled with resin composite. Three microhardness measurements were made at each depth from 0.5 to 3.5 mm.

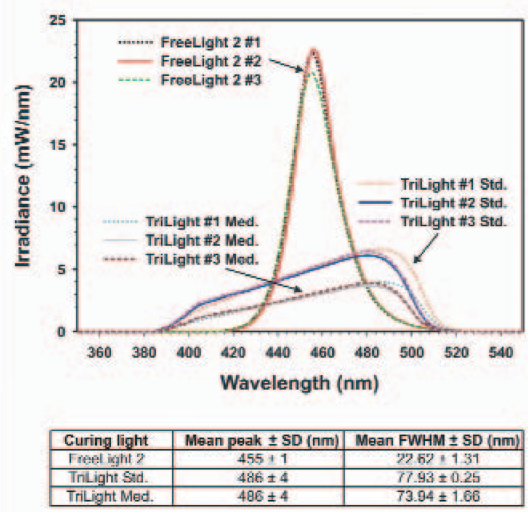

Figure 2: Mean (± standard deviation [SD]) spectral outputs from the 3 light-emitting diode curing lights (FreeLight 2) and the 3 quartz–tungsten–halogen curing lights (TriLight) on high (standard) and medium power settings. FWHM = full-width half-maximum, Std. = standard, Med. = medium.

Materials and Methods

This study compared the ability of a second-generation LED light and a QTH light to cure 10 different resin composites. A commercially available high-power LED curing light (FreeLight 2, 3M ESPE) was compared with a conventional QTH light (TriLight, 3M ESPE) operated at the standard setting (high power) or the medium power setting. The standard setting represented a higher power QTH curing light and the medium setting represented a typical QTH curing light. Hansen and Asmussen[19] reported that the distance from the cusp tip to the floor of

Table 2 Mean (± standard deviation [SD])[a] irradiance from 3 light-emitting diode (LED) curing lights and 3 quartz–tungsten–halogen (QTH) curing lights on standard setting (high power) or medium setting (medium power) at 0, 2 and 9 mm from the end of the light guide

Curing light	Distance from light guide; mean irradiance ± SD (mW/cm²) 0 mm	2 mm	9 mm
LED light			
Unit 1	1293 ± 8	1119 ± 55	172 ± 19
Unit 2	1386 ± 4	1110 ± 56	157 ± 3
Unit 3	1393 ± 53	914 ± 99	142 ± 27
High power QTH light (standard setting)			
Unit 1	964 ± 35	873 ± 61	351 ± 34
Unit 2	908 ± 30	779 ± 8	254 ± 6
Unit 3	765 ± 89	661 ± 36	229 ± 5
Medium power QTH light (medium setting)			
Unit 1	567 ± 11	523 ± 2	204 ± 5
Unit 2	524 ± 12	442 ± 8	148 ± 2
Unit 3	464 ± 10	400 ± 4	148 ± 1

[a]*Mean of 3 recordings made on 3 separate days*

proximal preparations was at least 8 mm in 15% of maxillary molars. Therefore, to simulate clinical conditions where the end of the light guide is not in contact with the composite,[19,20] the composites were exposed at clinically relevant distances of 2 and 9 mm from the end of the light guide as follows: LED curing light for 50% of the composite manufacturers' recommended exposure time (designated A), QTH curing light on standard setting for 50% of the recommended exposure time (designated B), and QTH curing light on the medium setting for 100% of the recommended exposure time (designated C).

To provide a representative sample of each brand of light and to allow a valid comparison between them, 3 FreeLight LED and 3 TriLight QTH curing light units were used. The irradiance and spectral distribution from the end of each light guide were measured on 3 separate days during the study using a spectroradiometer with a cosine corrector attachment (USB 2000 and CC-3UV, Ocean Optics, Dunedin, Fla.). The spectrometer was calibrated against a National Institute of Standards and Technology (NIST, Gaithersburg, Md.) traceable light source (Ocean Optics LS-1-CAL) before the emission from the light units was recorded.

Ten different resin composites (**Table 1**) were chosen to represent currently available composites of shade A2 or lighter. Lighter shades were chosen because they may contain photosensitizers other than camphorquinone. The composites were packed into sectional moulds made from extracted human molar teeth (**Fig. 1**). A total of 6 moulds were used, and the composites and curing lights were used in random order with these 6 moulds. Each mould represented a Class I preparation 1.5 mm wide and 4.0 mm deep, surrounded by dentin. The other half of the mould was the unprepared flat surface of the tooth. After the composite had been packed in the mould, a thin Mylar polyester strip was placed over the composite, and the 2 halves of the mould were clamped together. After light curing for 50% or 100% of the recommended exposure time, the mould was opened and the Mylar strip was removed. The surface of the composite was lightly sanded with 600-grit silicon carbide paper, and the specimens were stored in a lightproof container at room temperature for 15 minutes before hardness testing.

A good correlation has been reported between Knoop microhardness and degree of conversion of the monomer within a resin.[21,22] Therefore, the Knoop microhardness [KHN] of the resins was measured to determine the ability of the curing lights to polymerize the resin composites. The microhardness was measured with a Tukon hardness tester (Wilson Mechanical Instrument Division, American Chain and Cable Company Inc., Bridgeport, Conn.), which used a Knoop diamond indenter to apply a 100-g load to each resin composite surface for 15 seconds.[17,23,24]

The KHN_{100gf} was measured 15 minutes after exposure to the curing light. Hardness was measured in the centre of the composite at depths of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 mm from the top of the composite closest to the light source. Three readings were taken: at the centre, right and left locations at each depth (**Fig. 1**), and the mean microhardness was calculated at each depth for each composite specimen.

The microhardness data at each depth within the composites were compared using repeated measurements analysis of variance, the Kruskal–Wallis test, the aligned rank test and distribution-free multiple comparisons.[25]

Results

Table 2 shows the irradiance for the curing lights at distances of 0, 2 and 9 mm from the end of the light guide.

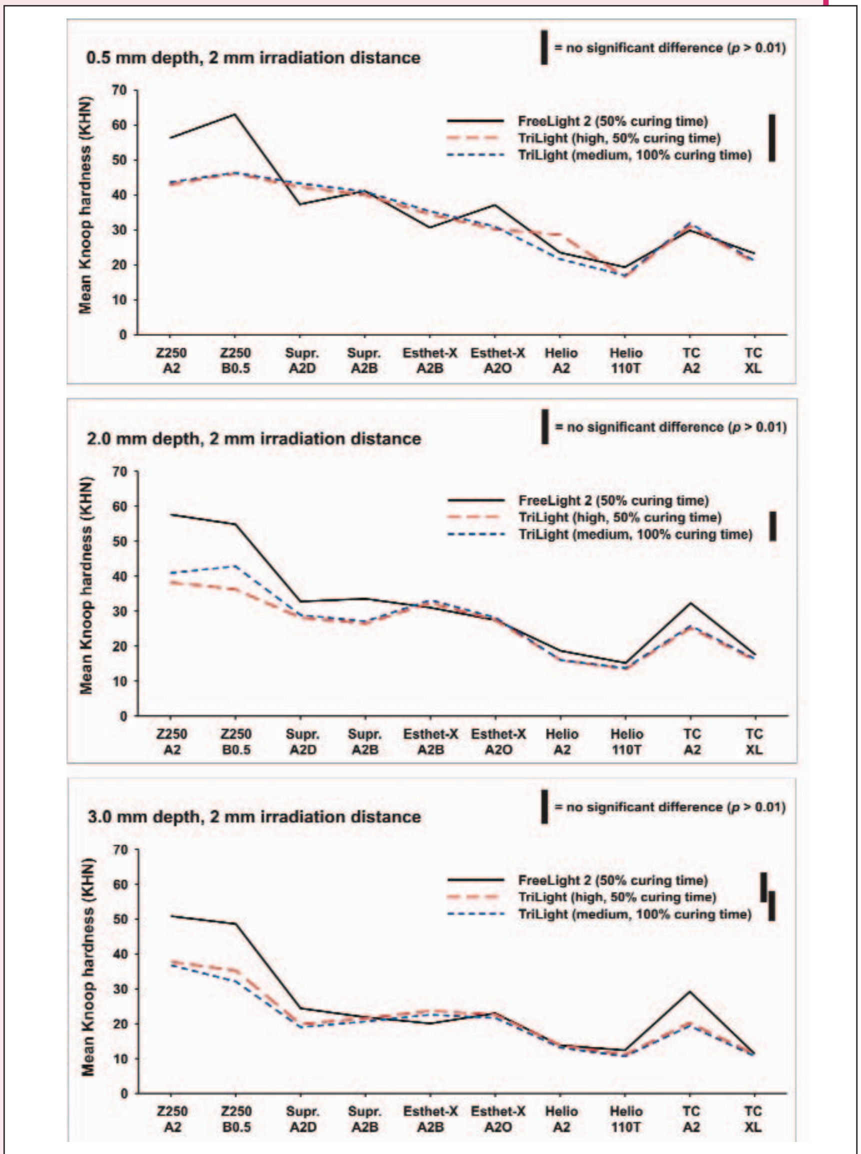

Figure 3: Effect of each combination of curing light and duration of exposure on the mean Knoop hardness (KHN_{100gf}) of every composite at depths of 0.5, 2.0 and 3 mm when irradiated at 2 mm from the end of the light guide. Statistical comparisons were made with the distribution-free multiple comparisons test. For details of the composites, see Table 1.

At both 0 and 2 mm from the end of the light guide, the irradiance was above 400 mW/cm² for the LED light and both settings of the QTH light. The irradiance dropped below 400 mW/cm² at a distance of 9 mm from the end of the light guides. The LED lights produced the highest irradiance measurements at distances of 0 and 2 mm, whereas the QTH at high power (standard setting) produced the highest irradiance at 9 mm. The LED curing light delivered a different spectral emission than the QTH light (**Fig. 2**). The spectral bandwidth, as shown by the full-width half-maximum (FWHM) values, was narrower for the LED light (22.62 nm) than the QTH light (> 70 nm). The peak irradiance values were also different: 455 nm for the LED and 486 nm for the QTH light.

Figure 3 illustrates the effect of each combination of curing light and duration of exposure on the mean KHN of every composite tested at selected depths (0.5, 2.0, and 3.0 mm), irradiated at a distance of 2 mm, and **Fig. 4** shows the results at the same depths at a distance of 9 mm. The change in the rank order of hardness for each composite, and between depths, illustrates that each curing light and time combination did not have the same effect on the microhardness of all composites. Repeated measurements analysis of variance indicated that all 2-way interactions and the 3-way interaction among curing light, depth and composite were statistically significant ($p < 0.01$). To eliminate type of composite as a factor, the curing ability of the lights was compared with non-parametric tests based on the ranked mean microhardness values instead of the mean microhardness values. At each depth, the Kruskal–Wallis test and the aligned rank test[25] showed significant differences between the values produced by the 3 combinations of curing light and duration of exposure (all $p < 0.001$). According to distribution-free multiple comparisons tests[25] and eliminating composite as a factor, **Table 3** shows that at 2 mm distance from the end of the light guide, the LED light used for 50% of the manufacturers' recommended exposure time (A) was ranked better than or equivalent to the QTH light at the high power setting used for 50% of the recommended time (B) or at the medium power setting used for 100% of the recommended time (C) ($p < 0.01$) to a depth of 3.5 mm within the composite. **Table 3** also shows that, for curing at a distance of 9 mm, the LED light (50% exposure time) was ranked better than or equivalent to the high-power QTH (50% exposure time) and the medium-power QTH light (100% exposure time) to a depth of 1.5 mm, beyond which the composites cured by the LED light for 50% of the exposure time were softer than when they were exposed to the other light–time combinations ($p < 0.01$).

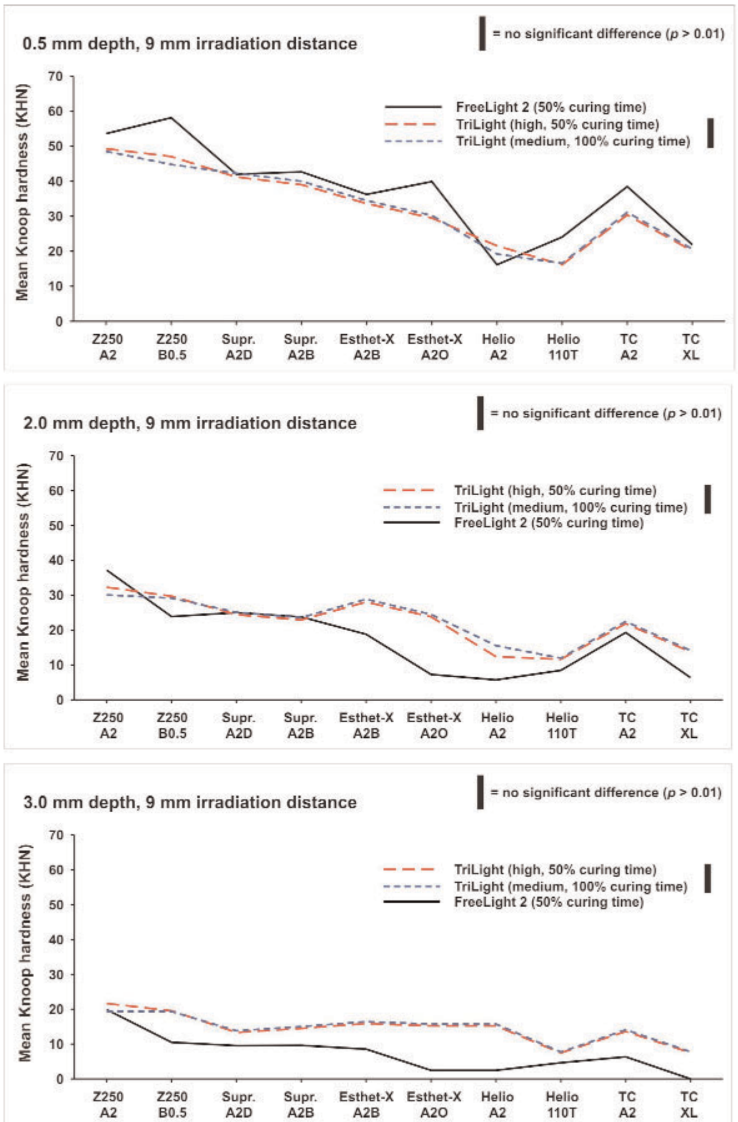

Figure 4: Effect of each combination of curing light and duration of exposure on the mean Knoop hardness (KHN_{100gf}) of every composite at depths of 0.5, 2.0 and 3 mm when irradiated at 9 mm from the end of the light guide. Statistical comparisons were made with the distribution-free multiple comparisons test. For details of the composites, see Table 1.

At both distances and at all depths, there were no significant differences ($p > 0.01$) between the microhardness values of composites cured by the QTH light operated on the high power setting for 50% of the recommended exposure time and composites exposed on the medium power setting for 100% of the recommended exposure time.

Discussion

In this study, a commercially available high-power LED curing light was able to cure 10 resin composites as well as a conventional medium-power QTH light, in half the exposure time recommended by the manufacturer. This was true to a depth of 3.5 mm when the light guide was 2 mm from the surface of the composite and to a depth of 1.5 mm at an extreme clinical distance of 9 mm from the end of the light guide (representing the bottom of a deep proximal box). Wiggins and others,[11] who evaluated the same brand of LED curing light, obtained similar results. They concluded that the FreeLight 2 LED curing light used for half the recommended exposure time produced a depth of cure equivalent to that produced by a first-generation LED light and a conventional QTH light when these lights were used for 100% of the recommended exposure time. As was also found in the present study, the LED light produced equivalent results to a high-power QTH light used for the same time (50% recommended time). However, Wiggins and others only tested resin composites made by the same manufacturer who produced the curing light, and it could reasonably be expected that the manufacturer of a curing light would ensure that their light would polymerize their own composites. Wiggins and others[11] used the International Organization for Standardization standard 4049:2000(E) scrape test[26] to determine the depth of cure, but this technique may overestimate the depth of cure and is not as sensitive as Knoop microhardness values for comparing the ability of different curing lights to polymerize resin composites.[27]

Figures 3 and **4** show that composites from different manufacturers responded very differently to each combination of curing light and exposure time, and the ranking of the microhardness produced by the 3 light–time combinations in this study was dependent on the depth where the microhardness of the composite was measured. This may indicate that the composites use different photosensitizers and that the narrow spectral output from the LED light was insufficient to activate the photosensitizers used in all the composites. The 10 resin composites were chosen to encompass a range of composite materials and photosensitizer components, especially in the lighter bleach shades. These shades may not use camphorquinone because it is yellow-coloured and is less suited for use in the bleach or translucent shades.

Table 3 Distribution-free multiple comparisons based on ranked sums showing significant differences ($p < 0.01$) between the 3 combinations of light and exposure time[a] at depths of 0.5 to 3.5 mm within the composite and irradiated at distances of 2 and 9 mm

	Rank		
Curing distance and depth	**1**	**2**	**3**
2 mm curing distance			
0.5 mm	A, B, C		—
1.0 mm	A, B, C		—
1.5 mm	A, B, C		—
2.0 mm	A	B, C	—
2.5 mm	A	B, C	—
3.0 mm	A, B	B, C	—
3.5 mm	A	B, C	—
9 mm curing distance			
0.5 mm	A	B, C	—
1.0 mm	A, B, C		—
1.5 mm	A, B, C		—
2.0 mm	B, C	A	—
2.5 mm	B, C	A	—
3.0 mm	B, C	A	—
3.5 mm	B, C	A	—

[a]A=FreeLight 2 light-emitting diode curing light for 50% of the manufacturer's recommended time; B = TriLight quartz–tungsten–halogen (QTH) curing light at the high power (standard) setting for 50% of the manufacturer's recommended time; C = TriLight QTH curing light at the medium setting for 100% of the manufacturer's recommended time.

Even though the spectral bandwidth of the LED light was narrower than that of the QTH light, the LED light did polymerize all 10 composites at the 2 mm distance. This result was reassuring since the photosensitizer components used in dental resins are proprietary and manufacturers are often unwilling to divulge the contents of their products. Although it is known that the Z250 composite (3M ESPE) uses camphorquinone and a tertiary amine as its photosensitizer component,[11] the results of this study support reports that other composites use alternative photosensitizers activated by wavelengths other than those that activate camphorquinone.[5] As might be expected, the Z250 composite, which is made by the manufacturer of the LED light, was well cured by the LED light, and the photosensitizer component of the Z250 composite appeared to be matched to the spectral output from the LED light. The fact that all the 2-way interactions and the 3-way interaction among curing light, depth and composite were statistically significant ($p < 0.01$) shows that the choice of composite (which may contain a range of photosensitizers) and the thickness of composite can have a significant effect in an evaluation and comparison of dental curing lights. Therefore, any future studies should test a range of composites and at different thicknesses.

The irradiance values at the tip of the light guide ranged from 1293 to 1393 mW/cm^2 for the LED lights used in this study, from 765 to 964 mW/cm^2 for the QTH lights at the high power setting, and from 464 to 567 mW/cm^2 for the QTH lights at the medium power setting. The reduction in irradiance at 9 mm from the tip of the light guide, especially for the LED light (**Table 2**), and the lower hardness values at this distance (**Fig. 4**) are of concern. Even when the light guide is held close to the tooth, the gingival increment of a Class II restoration may be 7 mm or more away from the end of the light guide,[19,20] and the composite may not be adequately cured when the irradiance level is so low. Thus, as the distance from the light guide increases and the depth of the preparation increases, it is recommended that the increment of composite to be cured be decreased to 1 mm.

While it is recognized that higher-power QTH lights are available, it was previously shown[28] that 55% of QTH lights used in dental offices delivered irradiance values less than 300 mW/cm^2. In another study,[29] 52% of QTH lights delivered less than 400 mW/cm^2. Thus, even on the medium power setting, the irradiance delivered by the QTH lights used in this study was probably greater than that delivered by the QTH curing lights in most dental offices. The manufacturers' recommended exposure times probably assume that the dentist is using an average medium- to low-power QTH light. This may explain why exposure times can be reduced when a higher-power QTH light or a high-power LED light is used. In this study, the QTH lights produced the greatest irradiance at 9 mm, which may explain why these units produced the hardest composites at this distance. This result may be due to the design of the light guide rather than the type of light source (LED vs. QTH), since the type of light guide has been shown to greatly affect irradiance as distance increases.[20]

Given the results for the 10 composites tested, a dentist could reduce exposure times by 50% when using the second-generation LED light or the high power QTH light used in this study and still achieve similar or better hardness values within the composite than would be produced if an average medium-power QTH light were used for the composite manufacturers' recommended curing time. Thus, the FreeLight 2 cordless LED curing light would be a suitable replacement for many of the QTH lights now being used in dental offices.

Conclusions

When curing at a distance of 2 mm from the surface of the composite, and eliminating the choice of composite as a factor, the second-generation high-power LED curing light operated for 50% of composite manufacturers' recommended exposure time produced resin composites that were harder than or statistically equivalent to composites exposed to a high-power QTH curing light operated for 50% of the recommended exposure time. When curing at a distance of 9 mm from the surface of the composite, the high-power QTH light delivered greater irradiance and produced harder resin composites at depths beyond 1.5 mm. At both distances the QTH light operated on the high power setting for 50% of the recommended exposure time produced composites that were as hard as when they were exposed on the medium power setting for 100% of the recommended exposure time. These findings may have an important bearing on efficient clinical time management, particularly with regard to incremental curing of deep restorations that require several layers of composite.

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Acknowledgements: *This study was partially supported by an unrestricted research grant from 3M ESPE, who also donated the curing lights, and by Dalhousie University, department of dental clinical sciences.*

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The authors have no declared financial interests in any company manufacturing the types of products mentioned in this article.

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