Evaluation of a Second-Generation LED Curing Light

• **Richard B.T. Price,** BDS, DDS, MS, FDS RCS (Edin), FRCD(C), PhD •
• **Corey A. Felix,** BSc, MSc •
• **Pantelis Andreou,** PhD •

Abstract

Background: *Light-emitting diode (LED) curing lights offer advantages over quartz–tungsten–halogen (QTH) lights, but the first-generation LED lights had some disadvantages.*

Purpose: *This study compared a second-generation LED light with a QTH light to determine which was better at photopolymerizing a variety of resin composites.*

Methods: *The ability of a LED light used for 20 and 40 seconds to cure 10 resin composites was compared with that of a QTH light used for 40 seconds. The composites were 1.6 mm thick and were irradiated at distances of 2 and 9 mm from the light guide. The Knoop hardness at the top and the bottom of each composite was measured at 15 minutes and 24 hours after irradiation.*

Results: *The different curing lights and irradiation times did not have the same effect on all of the composites ($p < 0.01$). For specimens analyzed 24 hours after irradiation, the LED light used for 20 seconds cured 5 of the composites as well as when the QTH light was used for 40 seconds ($p > 0.01$). When used for 40 seconds, the LED light cured 6 of the composites as well as when the QTH light was used ($p > 0.01$), and all 10 composites achieved more than 80% of the hardness produced with the QTH light.*

Conclusions: *This LED light could not polymerize all of the composites as well as the QTH light. However, when used for 40 seconds, it cured more than half of the composites as well as when the QTH light was used, and all of the composites achieved a hardness comparable to that produced with the QTH light.*

MeSH Key Words: *composite resins/chemistry; dental restoration, permanent/instrumentation; lighting/instrumentation; materials testing*

The photoinitiators used in most light-cured dental resins are activated by visible light of wavelengths between 400 and 515 nm.[1] Dentists can choose from a variety of light-curing units (LCUs) for photopolymerization of light-activated dental resins, such as conventional quartz–tungsten–halogen (QTH), light-emitting diode (LED), plasma arc or laser. The most common LCU is the QTH light.[2] Its bulb produces a broad spectrum of wavelengths, and an internal filter removes most of those that are not useful.[1,3] However, several surveys have shown that most QTH curing lights used in dental offices deliver inadequate light intensity.[4,5] This problem has been attributed to several factors, including fluctuations in line voltage, deterioration of the QTH light bulb, deterioration of the reflector or filter, contamination of the light guide, effects of disinfection procedures on the transmission of light through the light guide and malfunction of the photoconductive fibres in the light guide.[6–8] LCUs that use blue LEDs produce a narrow band of wavelengths, specifically chosen to excite the photoinitiators commonly used in dental resins.[3,9] LEDs last for thousands of hours, whereas a conventional QTH light bulb lasts for only 30 to 50 hours; in addition, LEDs convert electricity into light more efficiently, and they produce less heat.[1,3,8–11] These features may overcome some of the reported drawbacks of QTH curing lights,[4,5,7,12] and the potential of LED technology in this area is considered promising.[3,8,11,13–15] Nonetheless, the first generation of LED curing lights, which often contained multiple LEDs, had a relatively low power output, and they did not perform as well as conventional QTH lights,[9,16,17] especially when used to polymerize resins containing certain co-initiators in addition to camphorquinone.[18,19] Second-generation LED lights are now readily available. **Figure 1** shows the spectral output from the Freelight (3M ESPE, St. Paul, Minnesota) first-generation LED curing light, which uses 19 first-generation LEDs. In contrast, a second-generation LED curing light (UltraLume 2, Ultradent Products Inc., South Jordan, Utah) uses only 2 high-power second-generation LEDs. The second-generation light delivers a different spectral distribution with a greater power output (the area under the spectral curve) than the first-generation light and may therefore offer better performance and shorter curing times.

If a light-activated resin restoration does not receive sufficient total energy at the correct wavelengths from the LCU, the effects of wear may be increased,[20,21] there may be greater breakdown at the margins of the restoration,[20] decreased bond strength between the tooth and the restoration,[22] greater cytotoxicity,[23–26] reduced hardness[27–29] and lower dynamic elastic modulus.[30] Consequently, the dentist must use an LCU that delivers sufficient total energy at the correct wavelengths.[31–34]

The amount of light energy received at the top and the bottom of a resin composite restoration is affected by many variables, such as power density from the curing light, duration of exposure, design of the light guide, distance from the tip of the light guide to the restoration, and the composition, thickness, shade and opacity of the composite.[27,30,33,35–40] Consequently, the measured hardness at the top surface of a restoration is a poor indicator of the hardness at the bottom of the restoration.[4,34,41] However, the hardness values at the top and the bottom of a clinically representative thickness of resin composite can be used to compare the efficacy of different lights in curing a known thickness of resin composite.

Ideally, new types of dental curing lights should perform as well as, or better than, a conventional QTH light. It has been reported that a QTH light should deliver a minimum power density of 300 to 400 mW/cm² to adequately cure a 1.5- to 2-mm thickness of resin composite in the manufacturer's recommended curing time,[34,42,43] but this recommendation does not take into account the effects of the different spectral characteristics of QTH, LED, plasma arc and laser curing lights. Although the International Organization for Standardization depth-of-cure test #4049 could be used to compare the efficacy of different lights,[44] Knoop hardness (KHN) is reportedly better at discriminating between the efficacy of different light sources.[19] A good correlation has also been reported between KHN and the degree of conversion of the monomer within the resin.[45,46] As a guideline to determine if the bottom of a resin composite is adequately cured, it has been suggested that there should be no more than a 20% difference between the maximum hardness at the top of the composite and that at the bottom.[9,16,17,42,47–50] In addition, a bottom-to-top KHN ratio of 80% has been reported to correspond to a bottom-to-top degree-of-conversion ratio of 90%.[49] Therefore, the efficacy of curing lights might also be compared on the basis of bottom-to-top hardness ratios. Clinically equivalent lights would have no more than a 20% difference between the maximum hardness values achieved for each resin composite.

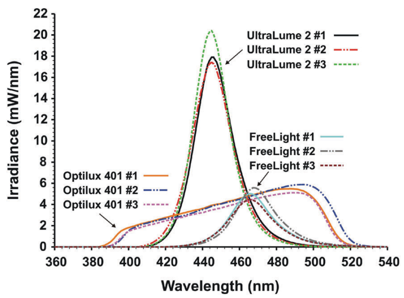
This study was undertaken to compare a second-generation LED curing light with a conventional QTH light (both in general clinical use), to determine which light was better at photopolymerizing a selection of 10 different resin composites. To determine whether the second-generation LED light could photopolymerize resin composites in less time than a conventional QTH light, the performance of the LED light was tested on the basis of 20 and 40 seconds of irradiation. The KHN at the top and the bottom of 1.6-mm thick composite specimens was used to compare the ability of the lights to cure resin composites at clinically relevant distances to a depth of 1.6 mm. The hypothesis was that, 24 hours after irradiation, the combined hardness at the top and bottom of resin composites irradiated by the LED light for 20 or 40 seconds at 2 and 9 mm distance would be greater than 80% of the hardness produced by a conventional QTH light used for 40 seconds.

Materials and Methods

The ability of a second-generation LED curing light (UltraLume 2, Ultradent Products Inc., South Jordan, Utah) to cure a selection of 10 multipurpose, flowable and posterior resin composites (**Table 1**) was compared with that of a conventional QTH light with an 11-mm diameter standard light guide (Optilux 401, Kerr Corp., Orange, California). The UltraLume 2 does not have a fibre optic light guide but instead has 2 LEDs covered by a disposable clear plastic lens at the end of the curing light (**Fig. 2**). Three UltraLume 2 units and three Optilux 401 units were used to provide a representative sample of each type of light. Each composite was placed into a 7-mm diameter hole in a steel washer, which was 1.6-mm thick. The washers were placed on a Mylar strip on a block of human dentin to simulate the floor of a preparation in a tooth (**Fig. 3**). To prevent the formation of an air-inhibited layer on the surface of the composite, another Mylar strip was placed on top of the composite. The specimens were irradiated (for 20 or 40 seconds with the LED units, and for 40 seconds with the QTH units) at distances of 2 and 9 mm from the light guide. The 2-mm distance was estimated as the shortest distance from the cusp tip to the composite at the bottom

Table 1 Composites used to compare different types of curing lights

Resin composite (shade)	Type	Manufacturer	Recommended curing time(s)
Multipurpose composites			
Vit-l-escence (TM)	Microhybrid	Ultradent Products Inc., South Jordan, Utah	20
Vit-l-escence (A2)	Microhybrid	Ultradent Products Inc., South Jordan, Utah	20
Esthet-X (A2)	Microhybrid	Dentsply, Milford, Delaware	20
Esthet-X (CE)	Microhybrid	Dentsply, Milford, Delaware	20
Herculite XRV (A2 dentin)	Hybrid	Kerr Corp., Orange, California	40
Flowable composites			
Filtek Flow (A2)	Hybrid	3M Dental Products, St. Paul, Minnesota	20
Revolution (A2)	Hybrid	Kerr Corp., Orange, California	20
PermaFlo (A2)	Hybrid	Ultradent Products Inc., South Jordan, Utah	20
Posterior composites			
Heliomolar (A2)	Microfill	Ivoclar-Vivadent AG, Schaan, Liechtenstein	40
Prodigy Condensable (A1)	Hybrid	Kerr Corp., Orange, California	40



Curing light	Mean peak ± SD (nm)	Mean FWHM ± SD (nm)
UltraLume 2	455.2 ± 0.3	23.78 ± 1.45
Optilux 401	491.3 ± 4.2	84.56 ± 2.58
FreeLight	467.1 ± 1.1	26.02 ± 1.19

Figure 1: *Mean spectral distributions of a first-generation LED curing light (FreeLight, with 19 LEDs), a second-generation LED curing light (UltraLume 2), and the QTH curing light (Optilux 401). Three units of each model were tested, and the data shown are means (± standard deviation) of 5 recordings for each unit. FWHM = full-width-half-maximum value.*

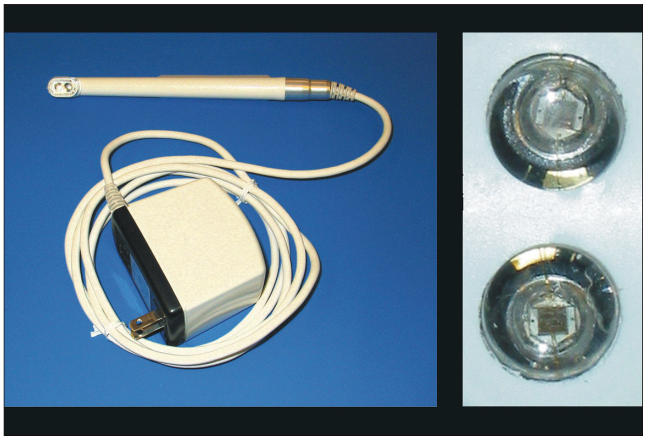


Figure 2: *A second-generation LED-curing light (UltraLume 2) and a magnified view of the 2 LEDs at the end of this light.*

of a Class I restoration. It has previously been reported that the distance from the cusp tip to the gingival floor of a proximal box of a molar tooth can exceed 7 mm.[36,51] Therefore, the 9-mm distance represented a clinical situation with a 7-mm-deep proximal box and the tip of the light guide 2 mm away from the tooth. The curing light guide was positioned directly above the composite specimen, with the tip of the light guide parallel to the sample. The resin composites were irradiated in a random sequence of curing lights and distances. Each LCU was used to cure one specimen of each composite for each test condition: 3 light–time combinations × 3 units of each light type × 2 distances × 10 composites for a total of 180 specimens.

Power density was measured after every 10 samples with a Cure Rite radiometer (Dentsply Caulk, Milford, Delaware). Spectral output and characteristics were recorded 5 times for each LCU with an Ocean Optics spectroradiometer (model USB 2000, Ocean Optics, Dunedin, Florida) attached to an integrating sphere (FOIS-1, Ocean Optics) and analyzed with OOIIrrad software (Ocean Optics). The spectrometer was calibrated according to a National Institute of Standards and Technology (Gaithersburg, Maryland) traceable light source (LS-1-CAL, Ocean Optics) before the spectral output from the LCUs was recorded. The mean spectral characteristics of each light are shown in **Fig. 1**, together with the mean peak output and the mean full-width-half-maximum (FWHM) values.

After each sample of composite had been cured, it was stored in a light-proof container in air at room temperature. The hardness was measured 15 minutes after irradiation. The samples were then stored in water at 37°C for 24 hours, at which time the hardness was measured again. The KHN at the top and the bottom of each composite specimen was measured at 10× magnification by means of a Tukon hardness tester (Wilson Mechanical Instrument

Table 2 **Mean power density (± standard deviation) and energy density measured with a Cure Rite radiometer at 0, 2 and 9 mm from the end of the light guide**

Curing light[a]	Curing time(s)	0 mm distance: Power density (mW/cm²)	0 mm distance: Energy density (J/cm²)	2 mm distance: Power density (mW/cm²)	2 mm distance: Energy density (J/cm²)	9 mm distance: Power density (mW/cm²)	9 mm distance: Energy density (J/cm²)
LED 1	20	652 ± 8	13.0	552 ± 2	11.0	267 ± 2	5.3
LED 2	20	711 ± 3	14.2	652 ± 4	13.0	302 ± 4	6.0
LED 3	20	788 ± 5	15.8	634 ± 3	12.7	305 ± 1	6.1
LED 1	40	652 ± 8	26.1	552 ± 2	22.1	267 ± 2	10.7
LED 2	40	711 ± 3	28.4	652 ± 4	26.1	302 ± 4	12.1
LED 3	40	788 ± 5	31.5	634 ± 3	25.4	305 ± 1	12.2
QTH 1	40	707 ± 2	28.3	623 ± 4	24.9	274 ± 4	10.9
QTH 2	40	734 ± 2	29.4	642 ± 3	25.7	295 ± 1	11.8
QTH 3	40	707 ± 5	28.3	632 ± 3	25.3	273 ± 2	10.9

[a]LED = second-generation light-emitting diode curing light (UltraLume 2), QTH = conventional quartz–tungsten–halogen curing light (Optilux 401). Three units of each type of curing light were tested.

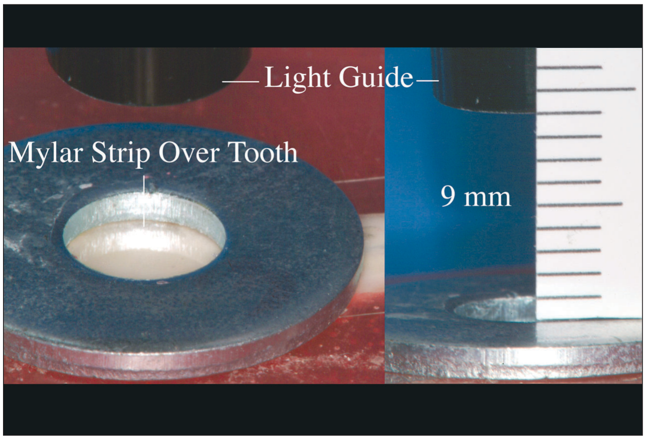


Figure 3: *Resin composite specimens were irradiated at distances of 2 and 9 mm from the light guide. Each composite was positioned in a steel washer over a flat tooth surface covered by a Mylar strip.*

Division, American Chain and Cable Company Inc., Bridgeport, Connecticut) with a Knoop diamond indenter that applied a 100-g load for 15 seconds.[9,16,46] The hardness measurements were repeated 3 times on each side of the composite, all within 1 mm of the centre. The Knoop hardness data were compared using a general linear model analysis with Sidak's adjustment for multiple comparisons.[52]

New designs of curing lights should perform as well as or better than the curing lights they are to replace. Therefore, $p < 0.01$ was chosen as the level of significance in this study, to ensure that conclusions regarding the choice of curing light and curing times could be made with a 99% level of confidence.

Results

The mean thickness of the resin composite specimens was 1.61 ± 0.07 mm, which was well within the 2-mm maximum thickness recommended for adequate curing of resin composites.[4,29,34,53] The mean power densities from the second-generation LED and QTH lights were very similar (**Table 2**), although the spectral bandwidths were quite different (**Fig. 1**). The area under the spectral curves in **Fig. 1** represents the total power (in milliwatts) emitted by the 3 first-generation LED lights (FreeLight), the 3 second-generation LED lights (UltraLume 2) and the 3 conventional QTH lights (Optilux 401). The first-generation LED lights produced a narrow bandwidth, with a FWHM value of 26.02 nm and a peak wavelength output at 467.1 ± 1.1 nm. The 3 second-generation LED lights all produced similar spectral bandwidths, ranging from 405 to 500 nm, with a mean FWHM value of 23.78 nm and a mean peak wavelength output at 445.2 ± 0.3 nm. The 3 QTH lights had a much wider spectral bandwidth, ranging from 385 to 530 nm, with a mean FWHM value of 84.56 nm and a mean peak wavelength output at 491.3 ± 4.2 nm. The peak irradiance and areas under the spectral curves of the second-generation LED lights were much greater than those of the first-generation LED lights (**Fig. 1**), which shows that the second-generation LED lights had a greater power output. The peak wavelength was also lower (445 nm) than that of the first-generation light (467 nm). The energy density (in joules per square centimetre) was calculated by multiplying the power density by the total curing time in seconds. Therefore, when the curing time was reduced by half for the second-generation LED unit (from 40 to 20 seconds), the energy density received by the composite resin was also reduced by half (**Table 2**).

The hardness values produced by the 3 QTH light units were very similar. The standard deviations of the differences in the hardness values produced by any 2 of these units used under the same conditions were at most 2 KHN. Similar results were obtained for the LED lights. These small differences in hardness values produced by the

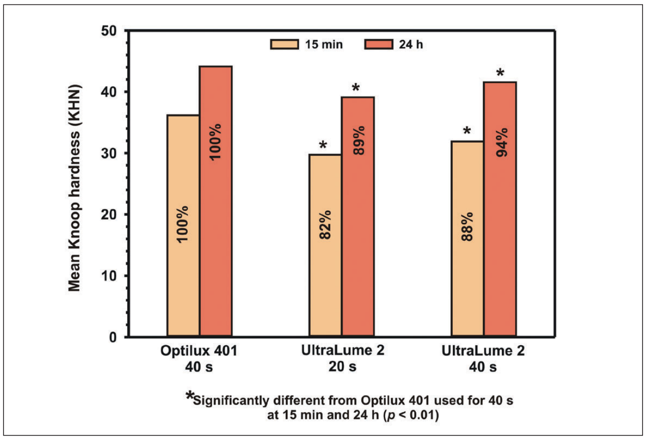


Figure 4: *Overall mean Knoop hardness (KHN) values (combined hardness values at the top and bottom at both distances for all 10 composites) for irradiation by both lights. The percent hardness values shown within the bars are relative to the hardness values obtained with the Optilux 401 QTH light at 15 minutes and 24 hours after irradiation.*

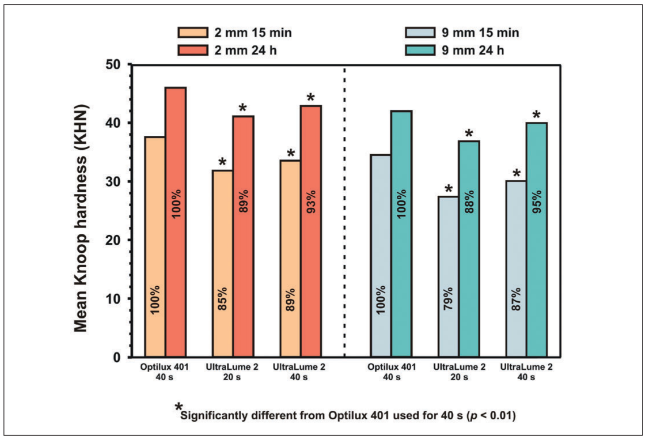


Figure 5: *Mean Knoop hardness (KHN) values (combined hardness values at the top and bottom of the 10 composites) at 2 and 9 mm from the tip of the light guide measured 15 minutes and 24 hours after irradiation. The percent hardness values shown within the bars are relative to the hardness values obtained with the Optilux 401 QTH light.*

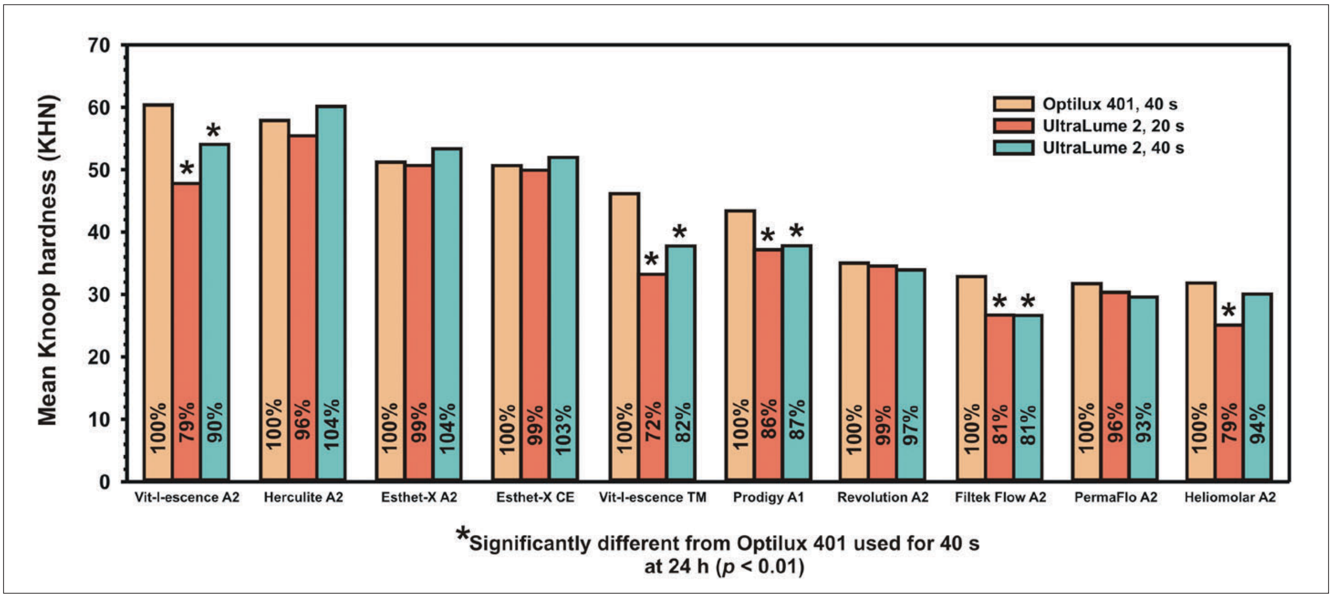


Figure 6: *Mean Knoop hardness (KHN) values for each composite (combined hardness values at the top and bottom at both distances from the tip of the light guide) measured 24 hours after irradiation. The percent hardness values shown within the bars are relative to the hardness values obtained with the Optilux 401 QTH light.*

3 examples of the same type of curing light were not considered clinically significant.

Figure 4 shows the overall mean KHN (the combined hardness values at the top and bottom at both curing distances for all 10 composites) after irradiation with the QTH curing light for 40 seconds and the second-generation LED curing light for 20 and 40 seconds. When the side and distance data of all the composites were combined, the overall mean KHN values were significantly different between the QTH light and the second-generation LED curing light ($p < 0.01$) at both 15 minutes and 24 hours after irradiation. **Figure** 4 also shows that the second-generation LED curing light, used for either 20 or 40 seconds, was able to produce overall (side, distance and composite data combined) mean hardness values at 15 minutes and 24 hours that were more than 80% of the values obtained after irradiation with a QTH light for 40 seconds.

When only the side and composite data were combined, at both 2 and 9 mm from the tip of the light guide, there was still a significant difference in mean hardness values obtained when the QTH light and the LED light were used (both curing times), at both 15 minutes and 24 hours after irradiation ($p < 0.01$) (**Fig.** 5). However, the 24-hour combined top and bottom hardness values for the LED light used for 20 and 40 seconds were greater than 80% of the 24-hour mean hardness values achieved with the QTH light at both 2 and 9 mm from the light guide (**Fig. 5**). When the LED light was used for 40 seconds, the mean hardness values at 15 minutes was greater than 80% of the 15-minute mean hardness values achieved with the QTH light at both 2 mm (89%) and 9 mm (87%) from the light guide. When the LED light was used for 20 seconds at 2 mm from the light guide, the combined top and bottom hardness value at 15 minutes was 85% of the hardness value achieved with the QTH light. For the same curing time of 20 seconds but at 9 mm from the light guide, the mean hardness value obtained with the LED light was 79% of that achieved with the QTH light, but this increased to 88% at 24 hours after irradiation. The percent hardness values of the LED light relative to the QTH light were similar at 2 and 9 mm from the composite (**Fig. 5**), which indicates that when the distance between the light guide and the composite was increased from 2 to 9 mm, the effects on hardness were similar for the 2 types of curing lights.

The multipurpose, flowable and posterior resin composites did not all behave similarly when irradiated by the QTH or the LED lights ($p < 0.01$) (**Fig. 6**). When used for 20 seconds, the second-generation LED curing light was able to produce, at 24 hours after irradiation, combined top and bottom hardness values in 5 of the 10 composites (Herculite XRV A2 dentin, Esthet-X A2, Esthet-X CE, Revolution A2 and PermaFlo A2) that were statistically equivalent to the hardness produced when the QTH light was used for 40 seconds. Seven of the composites (Herculite XRV A2 dentin, Esthet-X A2, Esthet-X CE, Prodigy Condensable A1, Revolution A2, Filtek Flow A2 and PermaFlo A2) achieved greater than 80% of the combined top and bottom hardness values obtained with the QTH light. When used for 40 seconds, the second-generation LED curing light produced combined top and bottom hardness values in 6 of the 10 composites (Herculite XRV A2 dentin, Esthet-X A2, Esthet-X CE, Revolution A2, PermaFlo A2, and Heliomolar A2) that were statistically equivalent to those obtained with the QTH light. By 24 hours after irradiation, all 10 composites had achieved greater than 80% of the combined top and bottom hardness values obtained when the QTH light was used for 40 seconds.

The hypothesis of this study — that 24 hours after irradiation, the combined hardness of the top and bottom of resin composites irradiated by the LED light for 40 seconds at 2 and 9 mm would be greater than 80% of the hardness produced by a conventional QTH light used for 40 seconds — was accepted for all composites tested to a depth of 1.6 mm. When the LED light was used for 20 seconds, the hypothesis was accepted for 7 of the 10 composites, but rejected for the remaining 3 composites (Vit-l-escence TM, Vit-l-escence A2, and Heliomolar A2).

Discussion

A new design of dental curing light should perform as well as a conventional light in good working order used under ideal conditions. This study compared the efficacy of a second-generation LED curing light (UltraLume 2) with that of a conventional medium-power QTH curing light (Optilux 401). A selection of multipurpose, flowable and posterior resin composites were irradiated at clinically representative distances of 2 and 9 mm from the light source, and hardness was measured after 15 minutes in air and after 24 hours in water at 37°C. Instead of measuring the hardness only at the top of the 1.6-mm-thick composite specimens, hardness was measured at both the top and the bottom of the specimens. At 2 mm the QTH lights delivered 623 to 642 mW/cm^2, which was much more than the power delivered by curing lights in most dental offices.[4,5] Because most composites require more than the manufacturer's recommended irradiation time when a QTH light delivering 300 mW/cm^2 is used for curing,[43] all the composites in this study were irradiated for 40 seconds by the QTH lights, receiving a mean energy of 25.3 J/cm^2 at 2 mm. Consequently, they should have been thoroughly cured by the QTH light and so should provide a rigorous comparator for specimens cured by the LED light.

The Knoop hardness value has been shown to correlate well with the degree of conversion of the resin[45,46]; therefore, the lower hardness values at 15 minutes than at 24 hours after irradiation indicate a lesser degree of monomer conversion within the resin composites at 15 minutes.[45,46] The increase in hardness after 24 hours in water at 37°C supports previous reports that post-irradiation polymerization occurs within the resin,[48,54–56] but this increase in hardness occurred in the specimens irradiated by both lights and did not compensate for inadequate initial polymerization.

A bottom-to-top KHN ratio of 80% corresponds to a reasonable bottom-to-top degree-of-conversion ratio of 90%.[49] Therefore, although there may be statistically significant differences between different lights, a 20% difference from the hardness of the composite specimens achieved with the QTH light was used to assess the clinical efficacy of the second-generation LED curing light. Unlike previous authors, who calculated the bottom-to-top hardness ratio on the basis of the hardness achieved at the top with the same light,[16,17,47,50] in this study the mean hardness at the top and bottom was compared with the mean hardness achieved using the QTH light. This allowed a comparison against the performance of the QTH light, rather than a comparison of bottom-to-top ratios for individual lights, which can be misleading. For example, if the KHN was

50 at the bottom and 60 at the top for light A, then the bottom hardness would be an acceptable 83% of the top hardness. If the KHN was 37.5 at the bottom and 45 at the top for light B, the bottom hardness would also be 83% of the top hardness, and the reader might think that lights A and B were similar. However, light B is producing a much softer composite at the top surface, and a better comparison would be the KHN of 37.5 at the bottom for light B with the KHN of 60 at the top for light A. This comparison would show that light B yielded unacceptable hardness values that were only 62.5% of the hardness achieved when the composite was irradiated with light A.

The overall combined mean hardness values achieved in the selection of multipurpose, flowable and posterior resin composites cured by each light in this study were significantly different from one another ($p < 0.01$). However, the overall hardness values produced when the LED lights were used for 20 and 40 seconds, at both 15 minutes and 24 hours after irradiation, were greater than 80% of the hardness values obtained when the QTH light was used for 40 seconds (**Fig. 4**). When the mean hardness values at the top and bottom of each composite irradiated at distances of 2 and 9 mm were examined after 24 hours in water at 37°C, all 10 composites irradiated by the second-generation LED curing light for 40 seconds had achieved a mean hardness that was greater than 80% of that produced by the QTH light used for 40 seconds. The LED light also produced hardness values greater than those obtained with the QTH light in 3 of the 10 composites, although not significantly so (**Fig. 6**). Thus, a dentist can reasonably expect that 40 seconds of curing with the UltraLume 2 will cure the selection of composites used in this study as well as a QTH light delivering 623 to 642 mW/cm^2.

Figure 6 illustrates how the multipurpose, flowable and posterior resin composites did not behave similarly ($p < 0.01$). After 40 seconds of irradiation by either light, Vit-l-escence A2, Herculite A2, Esthet-X A2 and CE were the hardest composites and, as expected, the flowable composites (PermaFlo A2, Revolution A2 and Filtek Flow A2) were the softest. The microfilled posterior composite Heliomolar A2 produced some of the lowest hardness values. There was little difference when Esthet-X, Revolution, Filtek Flow and PermaFlo were irradiated for 20 or 40 seconds with the LED light. This may be because the manufacturers' recommended curing time for all of these composites is 20 seconds, and irradiating them for a further 20 seconds with the LED light was unnecessary since it could not increase their hardness and degree of polymerization. For 6 of the composites (Esthet-X A2, Esthet-X CE, Herculite A2, PermaFlo A2, Revolution A2 and Heliomar A2), the second-generation LED light used for 40 seconds produced mean hardness values after 24 hours that were statistically equivalent to those achieved with the QTH light (**Fig. 6**). After 40 seconds, the mean total energy delivered by the 2 lights was similar: 24.5 J/cm^2 from the LED light and 25.3 J/cm^2 from the QTH light at 2 mm, 11.7 J/cm^2 from the LED light and 11.2 J/cm^2 from the QTH light at 9 mm. Therefore, the significant differences in hardness values for the remaining 4 composites irradiated by the QTH and LED lights might have been due to a mismatch between the spectral output of the LED lights (**Fig. 1**) and the spectral sensitivity of the composites.

When the second-generation LED curing light was used for 40 seconds and hardness was measured at 24 hours after irradiation, all 10 composites reached an acceptable hardness (i.e., at least 80% of the hardness achieved with a QTH curing light). When used for 20 seconds, the LED light was able to polymerize the composites to the extent that 24 hours after irradiation 7 of the 10 composites had reached more than 80% of the hardness value achieved by the QTH light (and 9 reached at least 79%). When the irradiation time was reduced by half, the total energy received by the composites was also reduced by half (**Table 2**). This reduction in total energy received by the composites (from a mean of 24.5 J/cm^2 to a mean of 12.2 J/cm^2 at 2 mm) resulted in hardness values of less than 80% for Vit-l-escence A2 and TM and Heliomolar A2 ($p < 0.01$). These results indicate that these composites require more than 20 seconds of irradiation with the LED light. This conclusion was supported by the lack of a significant difference in the hardness of the Heliomolar composite when it was irradiated for 40 seconds with the QTH or the LED curing light and the improved bottom–top hardness ratios when these composites were irradiated for 40 seconds (**Fig. 6**). Heliomolar was the only microfilled resin composite tested, and these results support previous reports that this type of composite requires more energy than hybrid or microhybrid composites for adequate polymerization,[16,28] perhaps because there is greater attenuation and scattering of light by the submicron filler particles.[2,8,9,35,42,48,57]

The spectral outputs shown in **Fig. 1** reveal that the second-generation LED light tested in this study was much more powerful than the first-generation LED light. The spectral output was also shifted toward shorter wavelengths (from a peak wavelength of 467 nm to a peak wavelength of 445 nm). The increase in power and the shift in spectral output may explain why this second-generation LED light performed better than in studies which used first-generation LED curing lights.[9,16,17] This second-generation LED light may therefore be able to cure composites that use photoinitiators and co-initiators which are activated by light at the lower wavelengths.[58] However, since the second-generation LED unit emitted very little light below 410 nm (**Fig. 1**), the QTH light (with a range from 385 nm to 530 nm) was better at curing composites containing photoinitiators and co-initiators which are activated at these lower wavelengths. Vit-l-escence A2 and TM, Prodigy A1 and Filtek Flow A2 probably contain such co-initiators, because at 24 hours after irradiation there were still significant differences in the hardness values achieved when the LED and QTH lights were used for 40 seconds (**Fig. 6**). Third-generation LED lights may produce more light at these lower wavelengths and so provide improved polymerization for these composites.

Curing light guides can have a focusing effect on the light output.[57] Depending on the design of the light guide, changes in the diameter of the light guide or increasing the distance from the light guide can have different effects on the power density.[42,51,57,59] The UltraLume 2 does not use a fibre optic light guide but instead has an oval lens to focus the light onto the tooth (**Fig. 2**). This lens may disperse light over a greater area than light from a standard light guide and may compromise the performance of the UltraLume 2 as the distance from the light guide increases. However, the power density from the QTH and LED curing lights was very similar at 0, 2 and 9 mm (**Table 2**). Even at 9 mm, the power density from both lights was close to 300 mW/cm^2, greater than the power density from many curing lights in dental offices measured at 0 mm.[4,5,7] Also, the percent hardness values achieved by the LED light relative to the QTH light were similar at 2 and 9 mm (**Fig. 5**). These results indicate that between 2 and 9 mm from the light guide, the lens on the UltraLume 2 had an effect on power density and the resultant composite hardness similar to that of the 11-mm standard light guide on the Optilux 401.

LED curing lights are relatively new, and it is not known how individual units will perform after several years of use in a dental office. Conversely, the performance of QTH curing lights is known to be adversely affected by years of use, and therefore the curing lights in many dental offices do not produce a power density as high as that delivered by the QTH light used in this study (in one study,[4] 55% of the units delivered less than 300 mW/cm^2, and in another,[5] 52% delivered less than 400 mW/cm^2). Therefore, the second-generation LED light tested here should outperform most QTH lights currently in use. If, as promised, LED curing lights last longer and maintain their power output longer than QTH lights, then the UltraLume 2 curing light (used for 40 seconds) would be a good curing light for a dental office. However, the 2 LEDs are located at the end of a hand-held wand (**Fig. 2**) that cannot by sterilized. Although disposable sleeves that cover the end of the wand can be used, infection control may be an issue with this light. Unlike other LED curing lights, the UltraLume 2 is not battery operated. This feature may be beneficial since battery-operated QTH and LED curing lights have been reported to lose some of their power output after repeated light exposures.[57,60]

If clinicians use this second-generation LED light for 20 seconds (delivering 12.2 J/cm^2 at 2 mm), they should be aware that not all composites will be cured as well as if they had been thoroughly cured by a conventional QTH curing light used for 40 seconds (receiving 25.3 J/cm^2 at 2 mm). However, because the combined top and bottom hardness value of each composite irradiated by the LED light for 40 seconds was greater than 80% of the hardness value achieved with a QTH light at both 15 minutes and 24 hours after irradiation, using this second-generation LED light for 40 seconds should ensure adequate polymerization of most composites to a depth of 1.6 mm. The manufacturer's product information does state that the UltraLume 2 cannot cure all resins, and this study did not test all resin composites currently available. Therefore, to be prudent, the dentist should always check that the curing light and the irradiation time used are adequate to polymerize the particular brand of resin used.

Conclusions

On the basis of the hardness measured at the top and the bottom of 1.6-mm thick specimens of 10 resin composites irradiated at clinically relevant distances of 2 and 9 mm from the light guide, the following conclusions were reached:

1. The second-generation LED curing light used for 40 seconds could polymerize 10 resin composites such that by 24 hours after irradiation all had reached an acceptable hardness (greater than 80% of the hardness achieved with the QTH curing light).
2. The LED light used for 20 seconds cured 5 of the composites as well as when the QTH light was used for 40 seconds ($p > 0.01$).
3. The LED light used for 40 seconds cured 6 of the composites as well as when the QTH light was used ($p > 0.01$).
4. Because the LED light did not polymerize all of the composites as well as the QTH light ($p < 0.01$), the dentist should check that the curing light and the irradiation time used are sufficient to adequately polymerize the resin used. ❖

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Dr. Price *is professor, department of dental clinical sciences, Dalhousie University, Halifax, Nova Scotia.*

Mr. Felix *is a dental student, Dalhousie University, Halifax, Nova Scotia.*

Mr. Andreou *is a biostatistician, community health and epidemiology, Dalhousie University, Halifax, Nova Scotia.*

Correspondence to: *Dr. Richard Price, Department of Dental Clinical Sciences, Dalhousie University, Halifax, NS B3H 3J5. E-mail: rbprice@dal.ca.*

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References

1. Rueggeberg F. Contemporary issues in photocuring. *Compend Contin Educ Dent Suppl* 1999; 25:S4–15.

2. Craig RG, Powers JM, editors. Restorative dental materials. 11th ed. St. Louis: Mosby; 2002. p. 704.

3. Althoff O, Hartung M. Advances in light curing. *Am J Dent* 2000; 13(Spec No):77D–81D.

4. Pilo R, Oelgiesser D, Cardash HS. A survey of output intensity and potential for depth of cure among light-curing units in clinical use. *J Dent* 1999; 27(3):235–41.

5. Martin FE. A survey of the efficiency of visible light curing units. *J Dent* 1998; 26(3):239–43.

6. Shortall AC, Harrington E, Wilson HJ. Light curing unit effectiveness assessed by dental radiometers. *J Dent* 1995; 23(4):227–32.

7. Miyazaki M, Hattori T, Ichiishi Y, Kondo M, Onose H, Moore BK. Evaluation of curing units used in private dental offices. *Oper Dent* 1998; 23(2):50–4.

8. Davidson CL, de Gee AJ. Light-curing units, polymerization, and clinical implications. *J Adhes Dent* 2000; 2(3):167–73.

9. Leonard DL, Charlton DG, Roberts HW, Cohen ME. Polymerization efficiency of LED curing lights. *J Esthet Restor Dent* 2002; 14(5):286–95.

10. Bass M. Optical Society of America. Handbook of optics. 2nd ed. Volume 1. New York: McGraw-Hill; 1995.

11. Craford MG, Holonyak N Jr, Kish FA Jr. In pursuit of the ultimate lamp. *Scientific American* 2001; 284(2):63–7.

12. Poulos JG, Styner DL. Curing lights: changes in intensity output with use over time. *Gen Dent* 1997; 45(1):70–3.

13. Nomura Y, Teshima W, Tanaka N, Yoshida Y, Nahara Y, Okazaki M. Thermal analysis of dental resins cured with blue light-emitting diodes (LEDs). *J Biomed Mater Res* 2002; 63(2):209–13.

14. Mills RW, Uhl A, Jandt KD. Optical power outputs, spectra and dental composite depths of cure, obtained with blue light emitting diode (LED) and halogen light curing units (LCUs). *Br Dent J* 2002; 193(8):459–63.

15. Asmussen E, Peutzfeldt A. Light-emitting diode curing: influence on selected properties of resin composites. *Quintessence Int* 2003; 34(1):71–5.

16. Dunn WJ, Bush AC. A comparison of polymerization by light-emitting diode and halogen-based light-curing units. *J Am Dent Assoc* 2002; 133(3):335–41.

17. Soh MS, Yap AU, Siow KS. Effectiveness of composite cure associated with different curing modes of LED lights. *Oper Dent* 2003; 28(4):371–7.

18. Uhl A, Mills RW, Vowles RW, Jandt KD. Knoop hardness depth profiles and compressive strength of selected dental composites polymerized with halogen and LED light curing technologies. *J Biomed Mater Res* 2002; 63(6):729–38.

19. Uhl A, Mills RW, Jandt KD. Photoinitiator dependent composite depth of cure and Knoop hardness with halogen and LED light curing units. *Biomaterials* 2003; 24(10):1787–95.

20. Ferracane JL, Mitchem JC, Condon JR, Todd R. Wear and marginal breakdown of composites with various degrees of cure. *J Dent Res* 1997; 76(8):1508–16.

21. St-Georges AJ, Swift EJ Jr, Thompson JY, Heymann HO. Curing light intensity effects on wear resistance of 2 resin composites. *Oper Dent* 2002; 27(4):410–7.

22. Lee SY, Greener EH. Effect of excitation energy on dentine bond strength and composite properties. *J Dent* 1994; 22(3):175–81.

23. Caughman WF, Caughman GB, Shiflett RA, Rueggeberg F, Schuster GS. Correlation of cytotoxicity, filler loading and curing time of dental composites. *Biomaterials* 1991; 12(8):737–40.

24. Chen RS, Liuiw CC, Tseng WY, Hong CY, Hsieh CC, Jeng JH. The effect of curing light intensity on the cytotoxicity of a dentin-bonding agent. *Oper Dent* 2001; 26(5):505–10.

25. de Souza Costa CA, Hebling J, Hanks CT. Effects of light-curing time on the cytotoxicity of a restorative resin composite applied to an immortalized odontoblast-cell line. *Oper Dent* 2003; 28(4):365–70.

26. Franz A, Konig F, Anglmayer M, Rausch-Fan X, Gille G, Rausch WD, and others. Cytotoxic effects of packable and nonpackable dental composites. *Dent Mater* 2003; 19(5):382–92.

27. Caldas DB, de Almeida JB, Correr-Sobrinho L, Sinhoreti MA, Consani S. Influence of curing tip distance on resin composite knoop hardness number, using three different light curing units. *Oper Dent* 2003; 28(3):315–20.

28. Eliades GC, Vougiouklakis GJ, Caputo AA. Degree of double bond conversion in light-cured composites. *Dent Mater* 1987; 3(1):19–25.

29. Correr Sobrinho L, De Goes MF, Consani S, Sinhoreti MA, Knowles JC. Correlation between light intensity and exposure time on the hardness of composite resin. *J Mater Sci Mater Med* 2000; 11:361–4.

30. Harris JS, Jacobsen PH, O'Doherty DM. The effect of curing light intensity and test temperature on the dynamic mechanical properties of 2 polymer composites. *J Oral Rehabil* 1999; 26(8):635–9.

31. Nomoto R. Effect of light wavelength on polymerization of light-cured resins. *Dent Mater J* 1997; 16(1):60–73.

32. Nomoto R, Uchida K, Hirasawa T. Effect of light intensity on polymerization of light-cured composite resins. *Dent Mater J* 1994; 13(2):198–205.

33. Rueggeberg FA, Caughman WF, Curtis JW Jr, Davis HC. Factors affecting cure at depths within light-activated resin composites. *Am J Dent* 1993; 6(2):91–5.

34. Rueggeberg FA, Caughman WF, Curtis JW Jr. Effect of light intensity and exposure duration on cure of resin composite. *Oper Dent* 1994; 19(1):26–32.

35. Ruyter IE, Oysaed H. Conversion in different depths of ultraviolet and visible light activated composite materials. *Acta Odontol Scand* 1982; 40(3):179–92.

36. Yearn JA. Factors affecting cure of visible light activated composites. *Int Dent J* 1985; 35(3):218–25.

37. Curtis JW, Jr., Rueggeberg FA, Lee AJ. Curing efficiency of the Turbo Tip. *Gen Dent* 1995; 43(5):428–33.

38. Tanoue N, Koishi Y, Matsumura H, Atsuta M. Curing depth of different shades of a photo-activated prosthetic composite material. *J Oral Rehabil* 2001; 28(7):618–23.

39. McCabe JF, Carrick TE. Output from visible-light activation units and depth of cure of light-activated composites. *J Dent Res* 1989; 68(11):1534–9.

40. Shortall AC, Wilson HJ, Harrington E. Depth of cure of radiation-activated composite restoratives — influence of shade and opacity. *J Oral Rehabil* 1995; 22(5):337–42.

41. Price RB, Dérand T, Loney RW, Andreou P. Effect of light source and specimen thickness on the surface hardness of resin composite. *Am J Dent* 2002; 15(1):47–53.

42. Shortall AC, Harrington E. Effect of light intensity on polymerisation of three composite resins. *Eur J Prosthodont Restor Dent* 1996; 4(2):71–6.

43. Fan PL, Schumacher RM, Azzolin K, Geary R, Eichmiller FC. Curing-light intensity and depth of cure of resin-based composites tested according to international standards. *J Am Dent Assoc* 2002; 133(4):429–34.

44. International Standard 4049. Dentistry-polymer-based filling, restorative and luting materials. Geneva, Switzerland: International Organization for Standardization, 2000.

45. Rueggeberg FA, Craig RG. Correlation of parameters used to estimate monomer conversion in a light-cured composite. *J Dent Res* 1988; 67(6):932–7.

46. Ferracane JL. Correlation between hardness and degree of conversion during the setting reaction of unfilled dental restorative resins. *Dent Mater* 1985; 1(1):11–4.

47. Yap AU, Seneviratne C. Influence of light energy density on effectiveness of composite cure. *Oper Dent* 2001; 26(5):460–6.

48. Pilo R, Cardash HS. Post-irradiation polymerization of different anterior and posterior visible light-activated resin composites. *Dent Mater* 1992; 8(5):299–304.

49. Wilson BM, Bouschlicher M, Rueggeberg F, Mettenburg DJ. Correlation of composite bottom-to-top microhardness and conversion values. *J Dent Res* 2003; 82 (serial online), Special Issue A(Abstract # 950).

50. Yap AU, Wong NY, Siow KS. Composite cure and shrinkage associated with high intensity curing light. *Oper Dent* 2003; 28(4):357–64.

51. Price RB, Dérand T, Sedarous M, Andreou P, Loney RW. Effect of distance on the power density from two light guides. *J Esthet Dent* 2000; 12(6):320–7.

52. Sidak Z. Rectangular confidence regions for the means of multivariate normal distributions. *J Am Stat Assoc* 1967; 62:626–33.

53. Sakaguchi RL, Douglas WH, Peters MC. Curing light performance and polymerization of composite restorative materials. *J Dent* 1992; 20(3):183–8.

54. Davidson-Kaban SS, Davidson CL, Feilzer AJ, de Gee AJ, Erdilek N. The effect of curing light variations on bulk curing and wall-to-wall quality of two types and various shades of resin composites. *Dent Mater* 1997; 13(6):344–52.

55. Tantbirojn D, Versluis A, Cheng Y, Douglas WH. Fracture toughness and microhardness of a composite: do they correlate? *J Dent* 2003; 31(2):89–95.

56. Halvorson RH, Erickson RL, Davidson CL. Energy dependent polymerization of resin-based composite. *Dent Mater* 2002; 18(6):463–9.

57. Shortall AC, Harrington E. Effectiveness of battery powered light activation units. *Br Dent J* 1997; 183(3):95–100.

58. Park YJ, Chae KH, Rawls HR. Development of a new photoinitiation system for dental light-cure composite resins. *Dent Mater* 1999; 15(2):120–7.

59. Harrington L, Wilson HJ. Determination of radiation energy emitted by light activation units. *J Oral Rehabil* 1995; 22(5):377–85.

60. Rueggeberg F, Hackman ST. Light power loss with repeated exposure. *J Dent Res* 2003; 82 (Serial online), Special Issue A(Abstract # 635).