Light-Emitting Diode Polymerization Curing Lights: Attributes and Uses

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Abstract

The dental light-curing unit has become an essential piece of equipment in almost every dental office, but it often is not well understood. The goal of this article is to provide guidance on the key features (radiant power, tip area, radiant exitance, irradiance, and beam profile) that clinicians should look for when purchasing and using a curing light. The potential "blue light hazard" from curing lights and the existence of Occupational Safety and Health Administration regulations regarding the duties of employers to ensure that their employees are protected from "potentially injurious light radiation" are discussed.

Key Words: curing lights, light output, composite resin, polymerization, blue light hazard

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Introduction

When purchased, dental adhesives, resin cements, resin composites, sealants, and orthodontic resin cements are all "unfinished." Their clinical performance depends on how well they are used and light-cured in the mouth. Consequently, most dental offices use a light-curing unit (LCU) many times a day to photocure these resins. Although there are many articles in dental journals on the differences between various adhesives, resins, and cements, or on the numerous ways to place and contour composite resins, there often is little information about the curing light, the light-curing conditions, or how the light was used.

One of the most challenging places to reach with the light from the LCU is the gingival portion of a Class II proximal box. This region often is in shadow and is the furthest away from the light tip.[1] It is recommended that areas such as this receive longer exposure times than the occlusal aspects of the restoration.[2] **Figure 1** illustrates a clinical situation where the operator is light-curing a disto-occlusal (DO) restoration in a premolar tooth. Although the light tip is close to the tooth, the light tip is angled, and the bottom of the distal box is in shadow.

If the resin receives an insufficient amount of light, it will produce an undercured product. This can lead to premature failure,[3] increased bacterial colonization,[4] increased water sorption and solubility, increased surface roughness,[4] reduced mechanical properties, and increased wear[5] of the resin. The problem is further complicated by the fact that the surface of undercured resins **(Fig 2)** will feel hard at the top when scraped with a dental instrument, but they may be undercured or even soft at the bottom.[6,7] Despite the importance of light-curing, the description of the light-curing procedure often is condensed into little more than "and then you light-cure for 10 seconds."[8] In addition, the procedure is sometimes delegated to an assistant who has limited knowledge or access to the tooth and who also may be unaware of the importance of light curing.

Since the dentist cannot examine the inside or bottom surface of the resin restoration, they have no way of knowing that the resin has been undercured at the bottom or inside the restoration. Instead, they must assume that if the instructions for use were followed, the resin will be adequately cured at the bottom. Some also mistakenly believe that, given time, the resin at the bottom will eventually fully cure. Consequently, it is not surprising that the gingival portion of a Class II proximal box is also the region where most Class II resin restorations fail due to secondary caries.[9]

In addition to the fact that the LCU often is poorly described,[10] the light-curing conditions that are used in almost all laboratory studies on dental restorative resins, resin cements, or bonding usually are conducted under ideal conditions that may not be clinically relevant.[2] No researcher would consider holding the LCU by hand while light-curing their specimens, or light-curing without looking at what they are doing because they know that this will increase the variability of their results; instead, the LCU is rigidly fixed above and perpendicular to the specimen. But in reality, patients move, and because many dentists and dental assistants do not watch what they are doing when they are light-curing, the light tip may inadvertently move off the intended target.[6,7] This will greatly reduce the amount of energy received and reduce the overall polymerization of the resin in the mouth compared to the results obtained in the laboratory.[4,11-15]

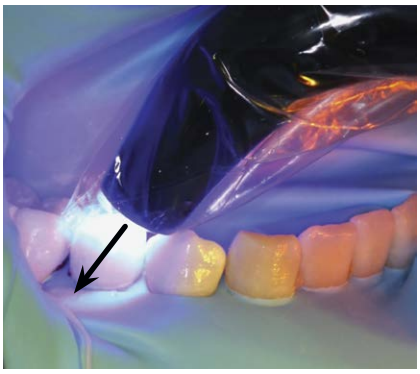
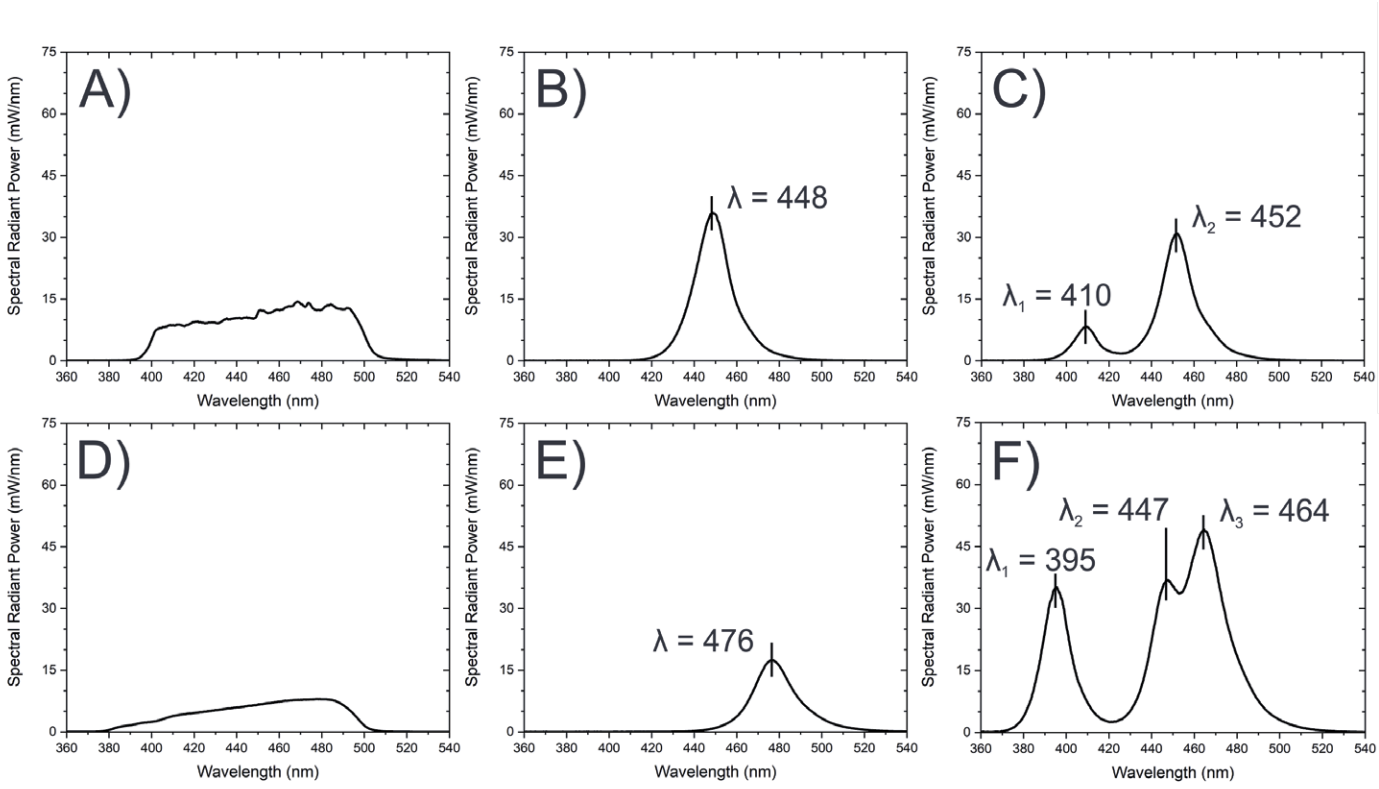


Figure 1: The angle of the light tip means that the bottom of the distal box of the restoration on the premolar tooth will be in shadow and very unlikely undercured.

Figure 2: Light-curing at this distance will still produce a surface that is hard at the top, but the bottom of the restoration likely will be undercured.

Figure 3: Evolution of curing lights from a larger gun-style to those that are smaller and more ergonomic.



Figures 4a-4f: PAC light (a) and QTH light (d) each emit a broad spectrum of light. Lights (b) and (e) are LED curing lights that emit light with a single peak wavelength (e.g., at 448 or 476 nm). In contrast, the broad-spectrum LED lights (c) and (f) emit a broader range of wavelengths and have multiple wavelength peaks from 395 to 464 nm depending on the LCU.

Defining Broad-Spectrum LED Curing Lights and Their Uses

The Polywave Bluephase (Ivoclar Vivadent; Amherst, NY), Valo and Valo Grand (Ultradent Products; South Jordan, UT), SmartLite Pro with PolyCure tip (Dentsply Sirona; Charlotte, NC), Translux 2Wave (Kulzer; South Bend, IN), and The Light 405 (GC America; Alsip, IL) are several currently available broad-spectrum LED curing light systems. **Figure 3** shows the progression of Ivoclar's Bluephase curing lights. As the battery, optical, and ergonomic designs have improved, this range has evolved from large gun-style lights to small ergonomic curing lights such as the Bluephase Style, G4, and PowerCure.

Features

The Bluephase G4, Bluephase PowerCure, Valo, Valo Grand, and SmartLite Pro all have excellent light beam profiles, but only the Bluephase and Translux 2Wave have light guides that can be autoclaved. Both the battery-operated and the corded versions of the Valo and the Valo Grand lights have a low-profile head with a scratch-resistant lens. The Valo has a 9.6-mm diameter active light tip, whereas the Valo Grand has a wider 11.6-mm diameter tip. The Teflon seals make cleaning easy, and the unibody aluminum construction makes these lights very durable. As an added benefit, the cordless version runs from two inexpensive batteries; this is in sharp contrast to other lights, whose replacement batteries can cost hundreds of dollars. The SmartLite Pro has an easily cleaned metal body, as well as a modular design that enables it to accommodate interchangeable tips for a variety of clinical situations.

Range of Wavelengths

PAC and QTH lights: Previously, most LCUs used a plasma arc (PAC) or a quartz tungsten halogen (QTH) bulb as the light source. The light from these relatively large-corded PAC and QTH sources is heavily filtered so that they emit a broad spectrum of violet and blue light that can activate a wide range of photoinitiators. Almost all dental LCUs now use light-emitting diodes (LEDs) to produce light. Although the blue light from all these different dental LCUs may appear the same to the human eye, when the light output is examined using a spectrophotometer, it can be seen that the emission spectra (wavelengths) emitted from these LED LCUs are quite different, both from each other and from PAC and QTH units **(Figs 4a-4f)**. In **Figures 4a and 4b**, the PAC and QTH lights emit a broad spectrum of light that will activate all currently available initiators.

Single-peak wavelength lights: In sharp contrast, the single-peak wavelength LED curing lights deliver only a narrow range of wavelengths **(Figs 4b & 4e)** that primarily activate the camphorquinone (CQ) photoinitiator used in most resin-based composites (RBCs). However, several resin manufacturers now include additional photoinitiators, such as trimethylbenzoyl diphenylphosphine oxide (Lucirin TPO, BASF AG; Florham, NJ) and Ivocerin (Ivoclar Vivadent), that are less yellow than CQ and allow lighter shades of resin to be produced.[16] These initiators react faster than CQ, thus allowing shorter exposure times. **Figure 5** shows that Lucirin TPO is most sensitive to ultraviolet or violet light between 380 and 410 nm rather than to the longer wavelengths of light at 468 nm that primarily activate CQ.

Combination wavelength lights: Since conventional single-peak LED curing lights provide very little light below 420 nm, some curing lights use a combination of several different LED emitters to deliver a broader emission spectrum that has multiple wavelength peaks that correspond to the light outputs from the different types of LED emitters used in the curing light **(Figs 4c & 4f)**. These additional LED emitters produce light at lower wavelengths in the violet range, which enables these LCUs to activate a wider range of photoinitiators.[17,18] The number and locations of these spectral emission peaks vary between manufacturers, as does each peak's relative contribution to the total power output **(Figs 4c & 4f)**. Although lights a, c, d, and f in **Figure 4** can initiate the Lucirin TPO, **Figure 5** shows that the new Ivocerin initiator can also be activated by a broader range of wavelengths, up to 460 nm; and thus lights a, b, c, d, and f will all work. However, LED light e will not activate the Ivocerin photoinitiator because this LCU delivers longer wavelengths of blue-green light that peak at 476 nm, and it does not emit sufficient light below 460 nm to activate the Ivocerin in a resin restoration.

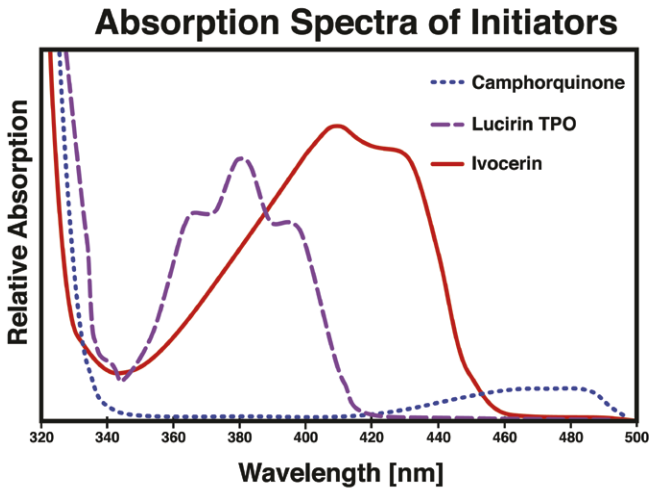


Figure 5: Absorption spectra of camphorquinone, Lucirin TPO, and Ivocerin initiators used in dental resins.

Unless the LCU is carefully designed, the addition of a variety of different wavelength LED emitters in the LCU may negatively affect the uniformity of the light beam from the LCU.[19-21] This lack of light homogenization and uniformity will then change both the irradiance and wavelengths of light received at different locations across the restoration. This will adversely affect the polymerization of the RBC, its bond strength, overall strength, color stability, and wear resistance, and will increase the amount of chemicals leaching from the partially cured resin.[17,21-23]

Power, Irradiance, and Emission Spectra

Clinicians should be aware that there is a large range in power and wavelengths emitted by curing lights. The light output from some curing lights is not uniform. A single irradiance value does not describe the output from the curing light.

Most light tips are circular in shape. Since the area of the light tip is derived from πr^2, even small changes in the effective tip diameter will have a substantial effect on the area, the radiant exitance from the light tip, and the irradiance received. For example, reducing the effective tip diameter from 10 to 7 mm will halve the tip area from 78.6 to 38.5 mm^2. Thus, if the same radiant power (mW) is emitted from both lights, halving the tip area will double the irradiance (mW/cm^2).

Light output from the Bluephase G4 and PowerCure: To determine the radiant power, the radiant exitance (the irradiance at the light tip), and the emission spectra from the Bluephase G4 and the Bluephase PowerCure **(Fig 6)**, their light outputs were recorded using a 6-inch integrating sphere (Labsphere; North Sutton, NH) connected to a fiberoptic spec-

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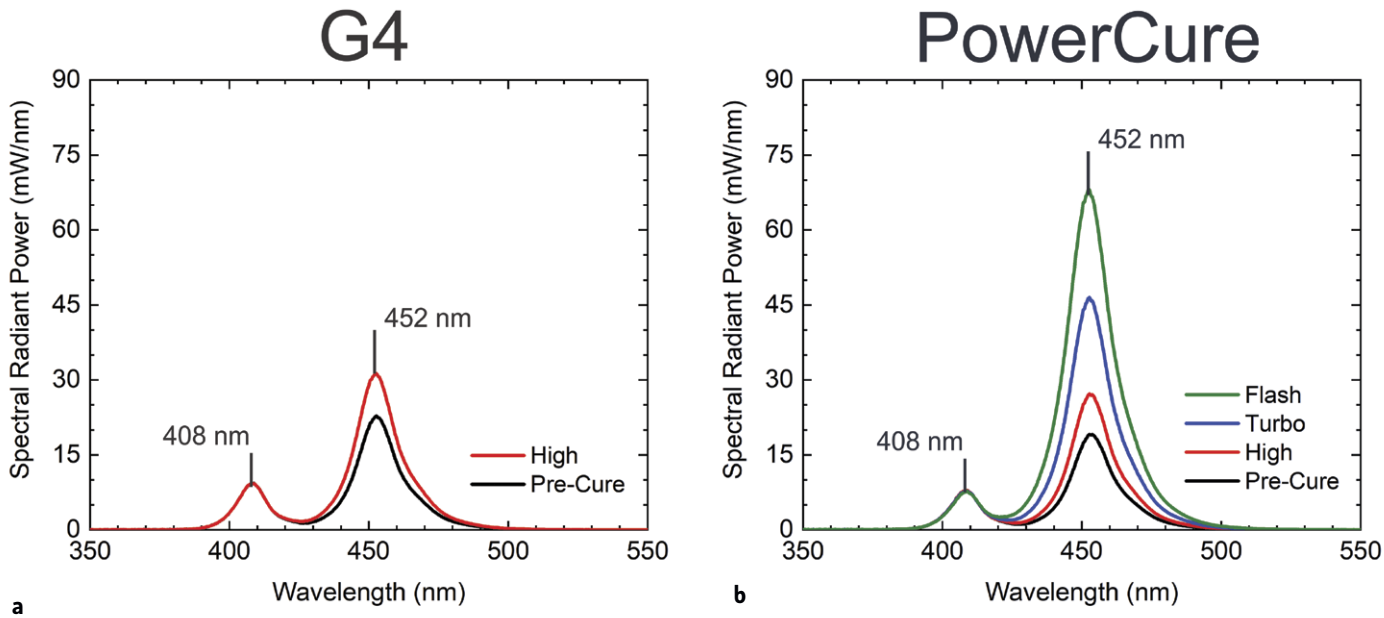
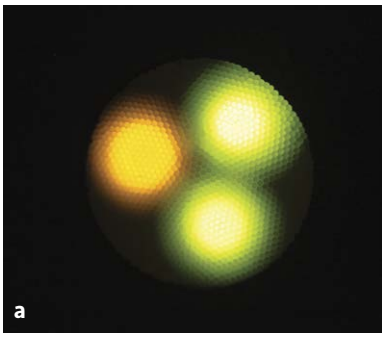
Figure 6: Bluephase G4 and Bluephase PowerCure, with an optional integrated light meter in the charging base.

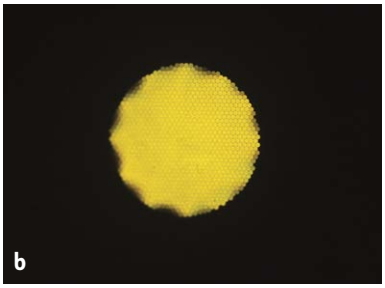
trophotometer (Ocean Insight; Largo, FL). Five measurements were made and averaged with the tip of the LCUs positioned at the aperture of the integrating sphere. Both the Bluephase G4 and the Bluephase PowerCure lights delivered light with the same wavelength emission peaks at 408 and 452 nm. The Bluephase G4 has an active tip diameter of 8.8 mm; this corresponds to an active tip area of 61 mm^2. Since the mean radiant power output was 758 mW, the mean irradiance value from the Bluephase G4 was 1243 mW/cm^2. The manufacturer states that the Bluephase G4 should deliver 1200 mW/cm^2 +/- 10%, which means that the G4 light tested met its specifications. The Bluephase PowerCure has a smaller effective tip diameter of 8.0 mm. This corresponds to a tip area of 50 mm^2, which is 11 mm^2 or 18% smaller than the G4 tip diameter. Since the mean radiant power output was 1515 mW, the average irradiance value from the Bluephase PowerCure in the 3-second mode was 3030 mW/cm^2. The manufacturer states that the Bluephase PowerCure light should deliver 3050 mW/cm^2 +/- 10%, which means that the light tested also met its specifications. Interestingly, **Figures 7a and 7b** show that two different settings on the G4 and the four settings on the PowerCure all delivered the same amount of violet light. It is only the amount of blue light that changes with the different settings; this may be because the manufacturer recognizes that longer wavelengths of blue light penetrate more deeply into the RBC than the violet light. Thus, delivering more violet light on the high output settings to light-cure 4-mm thick increments of an RBC is inefficient and will only produce more heat. The manufacturer has likely designed the LCU to deliver sufficient violet light to provide additional curing to the resin that is close to the surface. They recognize that due to the limited penetration of the violet light, the resin at the bottom 4 mm of the RBC will be mostly cured by the blue light component from the LCU.[24]

Differences in emission uniformity: The clinician can visualize some differences in the emission uniformity from curing lights by looking at the light output through orange blue-blocking glasses. **Figure 8a** shows an example where the light

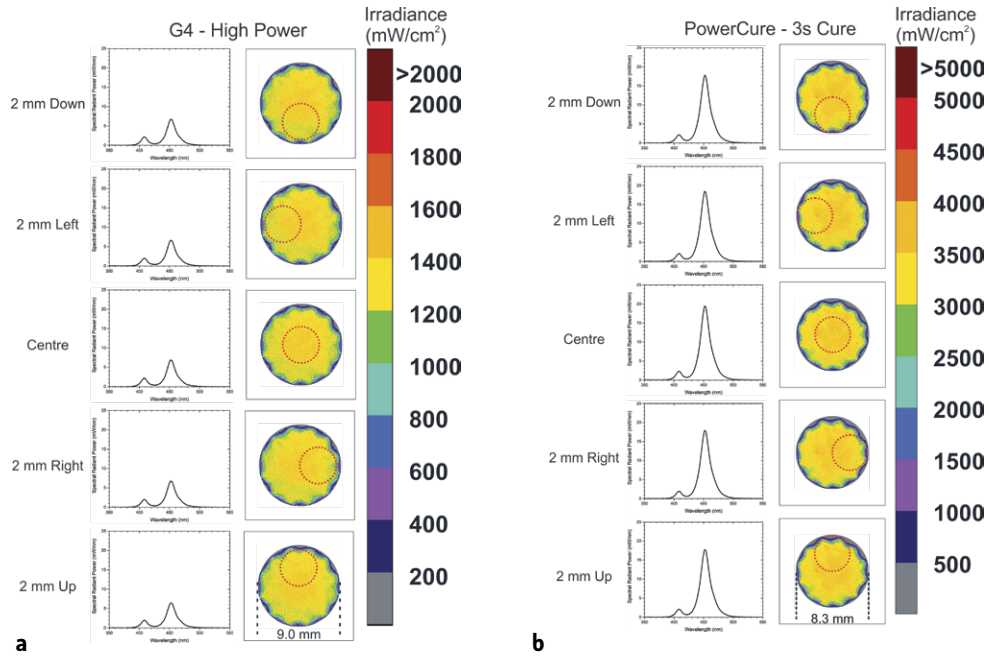


Figures 7a & 7b: Both the Bluephase G4 (a) and the PowerCure (b) have emission spectra with two-wavelength peaks, ~408 and 452 nm. Note that the violet component at 408 nm does not change on the different power settings; only the blue light at 452 nm changes.





Figures 8a & 8b: Light output from two LCUs viewed through orange blue-blocking glasses. The light tip (a) is not homogenous, whereas the output from the Bluephase G4 (b) is homogenous.



Figures 9a & 9b: Beam profiles and emission spectra from the Bluephase G4 (a) and Bluephase PowerCure (b). The emission spectra were measured at the center and then 2 mm away from the center in the north, south, east, and west positions, represented by the red circles on the beam profiles. Both lights displayed a similar uniform light output across the light tip, but at different irradiance levels (note the different irradiance scales).

from an LCU that has three LEDs is not mixed very well at the light tip. Through the blue-blocking glasses, the viewer can clearly see the three LEDs, two of which emit blue light and a third that emits violet light. **Figure 8b** shows the Bluephase G4 light viewed through the same glasses. Although this LCU also emits both blue and violet light, the light emitted from the tip of this LCU appears to be mixed much more homogenously at the light tip.

Quantitative measurement: To quantitatively measure the light beam profiles from dental LCUs, their light outputs must be recorded with a laser beam profiler. This device uses a digital camera (SP620U, Ophir-Spiricon; Logan, UT) to produce a calibrated map of the light output from the LCU. **Figures 9 and 10** show that both the Bluephase G4 and the Bluephase PowerCure deliver very uniform beam profiles. To further examine the emission spectra at several points across the light tip of these LCUs, the light output was sampled across the tip using a 4-mm-diameter aperture placed at the entrance to the integrating sphere. The light output was then measured at the center and at 2 mm from the center in the north, south, east, and west positions, represented by the red circles on the images in **Figure 9**. It can be seen that the light emitted was almost the same at all five locations, confirming that the light output was evenly distributed across the light tips of both of these LCUs. When overlaid over a molar tooth **(Fig 10)**, the clinical relevance of the irradiance beam profiles from both the Bluephase G4 and the Bluephase PowerCure lights becomes evident. Both of these LCUs deliver a uniform irradiance across the light tip that will cover much of the molar tooth with direct light. However, at least two exposures would still be required to fully cover a veneer on a maxillary central incisor, or an extensive restoration that includes five or more surfaces of a molar tooth, with light.

Effective Polymerization Feedback Technology

Both the Bluephase G4 and the Bluephase PowerCure contain what the authors believe is a unique feature in curing lights. Called Polyvision by the manufacturer, this feature is described as "lane feedback" technology for curing lights and helps clinicians ensure a more effective polymerization of light-cured dental materials. Lights that contain Polyvision vibrate to alert the clinician when the curing-light tip moves away from the tooth and then automatically increases the exposure time. This feature will also automatically turn the light off if the tip strays too far from the tooth and onto the soft tissues. This technology also prevents the light from accidentally being shone into the eye. If the user does not want Polyvision, it can be turned off. Unfortunately, at present, according to the manufacturer's instructions for use, this feature does not work when a plastic infection-control barrier is placed over the light tip. This limitation has been confirmed by the authors.

To test Polyvision, 25 experienced dentists used a Bluephase G4 curing light without an infection-control barrier. The radi-

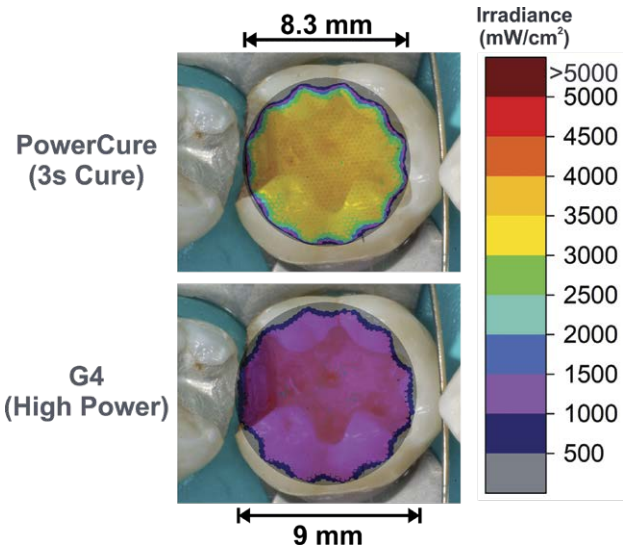


Figure 10: Beam profiles of the Bluephase G4 and Bluephase PowerCure on the same irradiance scale superimposed over a molar tooth. Note the higher irradiance and smaller tip diameter of the PowerCure.

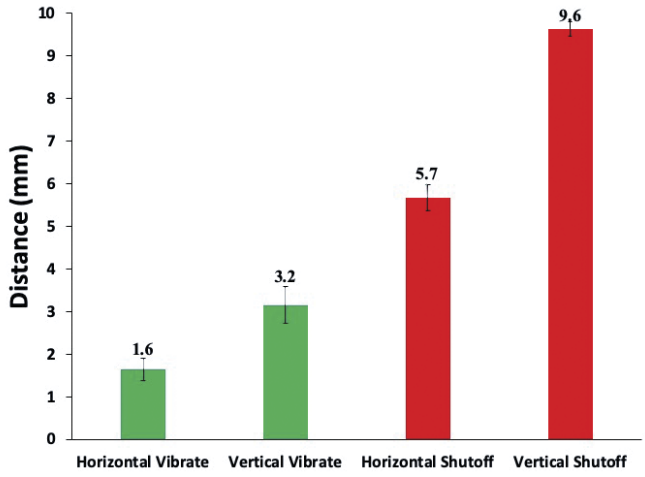


Figure 11: Mean (± standard deviation) distance from the central fossa when the Polyvision feature in the curing light first gave a vibration warning and then turned off the curing light.

ant exposure (J/cm²) delivered by these dentists to the anterior and posterior sensors on the MARC PS (BlueLight Analytics; Halifax, Canada) with and without Polyvision was compared using analysis of variance and Tukey post-hoc tests ($\alpha = 0.05$). On average, Polyvision gave the user a warning vibration when the light tip moved horizontally by 1.6 mm, and the LCU shut off when it moved 5.7 mm horizontally away from the cusp tip. When moved vertically, the LCU first vibrated when the tip was 3.2 mm away from the central fossa of a molar tooth and eventually turned off when the tip moved vertically by 9.6 mm from the central fossa, which is where the top surface of the resin likely would be located **(Fig 11)**. In 10 seconds, the mean radiant exposure delivered by the 25 participants to the anterior sensor on the MARC PS was 12.6 J/cm² without Polyvision and 13.1 J/cm² with it, and in the posterior region was 11.1 J/cm² without Polyvision, which improved to 12.1 J/cm² with it. Although this may not seem like much of an increase, if this feature can increase the amount of energy that these veteran clinicians can deliver by ~ 9% in the posterior region, it could potentially be even more beneficial for less experienced clinicians or their assistants. Twenty of the 25 dentists reported that Polyvision was useful and helped them keep the light tip on the tooth. They found that this feature was more noticeable and valuable in the posterior location, where access to the molar is more difficult. These technological advances are developing "smart" curing lights to help clinicians better cure their resins.

Blue Light Hazard from Dental LCUs

AMA and OSHA Recommendations

As long ago as 1985, the American Dental Association's Council on Dental Materials and Equipment recognized that the light from the relatively low-power dental LCUs that were available at that time could potentially cause ocular damage. It was recommended that appropriate protective filtering eyeglasses should be used when operating dental LCUs.[25] United States

"Since the area of the light tip is derived from πr^2, even small changes in the effective tip diameter will have a substantial effect on the area, the radiant exitance from the light tip, and the irradiance received."

DESIRABLE FEATURES IN A CURING LIGHT

When choosing a new curing light, the purchaser should consider/look for the following:

- Has the LCU been cleared/approved for use in your country?
- A slim ergonomic head that will allow perpendicular alignment over all of the restoration.
  - robust construction
- Simple, intuitive controls with a logical display of information.
  - cordless with user-replaceable batteries and low-battery warning
- Stable, reliable charging stand or base.
- Large tip size that will completely cover a molar or a maxillary central incisor.
- Optional smaller tip size for curing small restorations that are near soft tissues.
- Uniform light output.
- Broad emission spectrum that will allow the light to cure all available dental resins. However, if you know that the resins you use do not contain initiators that require violet light, then the inclusion of violet light is unnecessary and may even cause unnecessary heating.
- Irradiance is maintained over clinically relevant distances, even up to 10 mm away from the light tip.
- Sealed tip, handle, and controls for easy disinfection and cleaning.
- Optically clear and close-fitting infection control barrier that does not interfere with the operating features of the LCU.

Occupational Safety and Health Administration (OSHA) regulation 1910.133(a)(1) states, "The employer shall ensure that each affected employee uses appropriate eye or face protection when exposed to eye or face hazards from flying particles, molten metal, liquid chemicals, acids or caustic liquids, chemical gases or vapors, or potentially injurious light radiation."[26] OHSA also has a General Duty Clause requiring employers to furnish employees a place of employment free from recognized hazards that are causing or are likely to cause death or serious physical harm.[27] For this clause to be invoked, the hazard must be recognized, it must have the potential to cause serious physical harm, and there must be a feasible and useful method to correct it. Since we know that blue light can be harmful and that employees can be easily protected, all of these conditions apply when it comes to protecting employees from excessive exposure to blue light in the dental office. In 2016, the American Medical Association (AMA) expressed concerns that the blue light from the LEDs in streetlamps might suppress melatonin production, disrupt circadian rhythm, cause discomfort glare, and have detrimental environmental effects.[28] The AMA recommended that exposure to the blue-rich light from LED lights should be minimized. In April 2019, the French Agency for Food, Environmental and Occupational Health & Safety warned that powerful LED lights are phototoxic. The report recommended that the "maximum limit on short-term exposure to blue light should be reduced, only low-risk LED devices should be available to consumers."[29,30]

Most Significant Hazard in Dentistry

Based on animal and cell culture studies, the most significant blue light hazard to the retina occurs at 440 nm,[31] which is close to the maximum emission spectrum **(Fig 4)** from many dental LCUs.[23,32] The spectral radiant power (blue light output) from dental LCUs is much higher than that from household sources such as blue LED indicator lights, monitors, phones, and household white-light LEDs. The dental user may also focus their stare on the blue light when light-curing. Consequently, there are concerns that chronic exposure to blue light from high-power dental LCUs may cause ocular damage.[33-36] Although this potential hazard can be prevented by using appropriate eye protection, unfortunately, these items are not universally used.[2,6,17,37-40]

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Enhancing Clinical Success

There are several things that can and should be done to enhance clinical success when using a curing light.[17,23,41,42] In 2014, key opinion leaders from academia and industry met and developed a consensus statement about curing lights.[43] Key points can be summarized as follows:[41]

- Do not use any medical equipment on your patients that have not been approved/cleared for use in your country.
- Read and follow the instructions for use.
- Verify that the LCU you are using will polymerize the bottom of both light and dark shades of the RBC using the manufacturer's recommended exposure protocol, the thickness of the RBC, and the distance that you likely will use on your patients.
- Review the manufacturer's instructions for cleaning and use them to educate and train your staff on proper sanitization, disinfection, maintenance, charging, and use of the LCU. Regularly verify the output from the LCU using a radiometer that can measure both power and, if the tip diameter is entered, the irradiance from the LCU **(Fig 12)**.
- Keep the light tip clean. Gently remove any materials cured to the tip of the light using a >70% alcohol wipe and a plastic instrument.
- Use an approved protective barrier. Ensure that the barrier fits snugly over the light tip and avoid running a seam across the light tip, as this seam will negatively affect the light output.
- Regardless of the LCU that you use, it is crucial to use the appropriate clinical technique. Position the light tip close and perpendicular to the restoration **(Fig 13)** and avoid angles between the restoration and the light tip that will create shadows **(Figs 1 & 14)**.
- Watch what you are doing. Looking away is not recommended when light-curing because patients move, and the tip can easily stray off target. If you miss the target for just 1 second in a 3-second exposure, this represents a 33% reduction in the amount of light received.
- It is critically important to minimize ocular exposure to blue light by using an appropriate orange shield or orange glasses **(Fig 15)** to protect the eyes.
- When using a powerful LCU, prevent overheating and potential harm to soft tissues by directing a gentle stream of air over the tooth and using multiple short exposure times separated by 3 to 5 seconds for the heat to dissipate rather than a 20- or 30-second exposure.

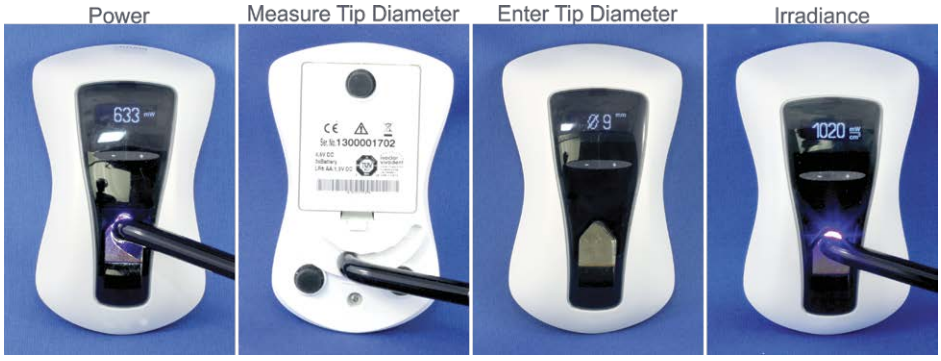

Figure 12: Using the gauge on the back of this radiometer, the tip diameter can be measured and entered into the meter to provide the irradiance from the measured power.

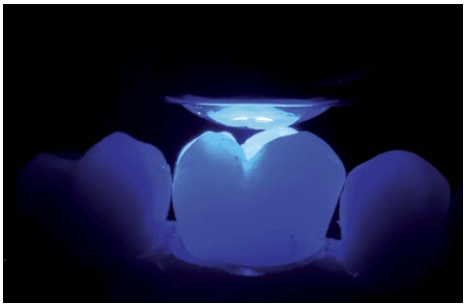

Figure 13: Position of the light tip close and perpendicular to the restoration.

Figure 14: Avoid angles between the restoration and the light tip that will create shadows.

Figure 15: Examples of eyewear, shields, cones, and paddles, critically important for protecting the eyes from blue light.

Summary

LED curing lights emit a different range of wavelengths compared to PAC or QTH curing lights. LED curing lights are not all the same—some are easier to disinfect, some are more durable, some have low-profile heads that allow better access to restorations, and some use two or more different types of LEDs to emit a broader range of wavelengths of both violet and blue light. The commonly used irradiance value is greatly affected by the light tip diameter and beam profile. A low-power light can still deliver a high irradiance merely by reducing the area of the light tip. Quality manufacturers homogenize the light from their LCUs so that the emission spectrum and radiant exitance are evenly distributed across the light tip. New technological advances can now warn the user if they move off the tooth. These improvements can increase the amount of light delivered and thus the quality of the final restoration.

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"Based on animal and cell culture studies, the most significant blue light hazard to the retina occurs at 440 nm, which is close to the maximum emission spectrum from many dental LCUs."