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Stability of the Light Output, Oral Cavity Tip Accessibility in Posterior Region and Emission Spectrum of Light-Curing Units

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Clinical Relevance

This study provides practitioners with information on the differences in spectral peak, irradiance, radiant exposure, output stability, mouth accessibility, and tip size for a variety of light-curing units, which can define the choice of proper equipment for clinical use.

SUMMARY

Objectives: This study evaluated the light output from six light-emitting diode dental curing lights after 25 consecutive light exposures without recharging the battery, tip accessibility in the posterior region, and light beam spread from light-curing units.

Methods: Irradiance, spectral peak, and radiant exposure were measured with the battery fully charged (Bluephase Style, ESPE Cordless, Elipar S10, Demi Ultra, Valo Cordless, and Radii-Cal) and monitored for 25 light exposures (each lasting 10 seconds). The tip diameter was measured to identify the beam size and the ability of the six light-curing units to irradiate all areas of the lower second molar in the standard output setting.

Results: Four curing lights delivered a single peak wavelength from 454 to 462 nm, and two (Bluephase Style and Valo Cordless) delivered multiple emission peaks (at 410 and 458 nm and 400, 450, and 460 nm, respectively). The irradiance and radiant exposure always decreased after 25 exposures by 2% to 8%, depending on the light unit; however, only ESPE Cordless, Valo Cordless, and Radii-Cal presented a statistical difference between the first and the last exposure. The tip diameter ranged from 6.77 mm to 9.40 mm. The Radii-Cal delivered the lowest radiant exposure and irradiance. This light was also unable to access all the teeth with the tip parallel to the occlusal surface of the tooth.

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Conclusion: Not all of the blue-emitting lights deliver the same emission spectra, and some curing lights delivered a lower irradiance (as much as 8% lower) after the 25th exposure.

INTRODUCTION

To overcome some of the problems associated with quartz-tungsten-halogen lights,[1,2] dental light-emitting diode (LED) curing lights were developed. According to Leprince and others,[3] LED curing lights offer the best option because they have a narrower emission spectrum with peak output close to the camphorquinone absorption peak of 470 nm and can be battery operated.

To achieve an adequate amount of polymerization of the resin material, practitioners should use curing lights that deliver the correct wavelengths to each resin composite.[4,5] Camphorquinone is the most commonly used photoinitiator in dental resins.[6] However, alternative photoinitiators with different peak absorptions have been added to the composition of some resin-based composites (RBCs) and resin cements to improve their mechanical behavior, depth of cure, and final color.[3,7] To deliver wavelengths of light that will activate more than one photoinitiator, some LED units deliver a light output that has two or more wavelength peaks, instead of a single emission peak (conventional LEDs).[2,8]

Another concern regarding dental light curing in the mouth is whether or not sufficient radiant exposure (sometimes incorrectly described as energy density) has been delivered to cure the resin composite.[4] The radiant exposure (J/cm^2) is the product of light irradiance (mW/cm^2) multiplied by the exposure time.[4,9] Depending on the brand and shade of the RBC, the radiant exposure required to adequately polymerize the RBC can range from 6 to 24 J/cm^2 for a 2-mm increment.[9,10] A handheld dental radiometer usually measures only the irradiance delivered at the tip end of the light-curing unit and not the radiant exposure received by the restoration.[9] The single irradiance value uses a method described in ISO 10650 standard (calculated from the quotient of the radiant power and light tip optical area) that is inversely proportional to the tip area[11]; in other words, small changes in the light-curing tip diameter will have a large effect on the irradiance.[12] Consequently, if the same radiant power is delivered, changing the tip diameter from 10 to 7 mm halves the tip area and doubles the irradiance.

LED lights consume low power and can be battery operated.[3,11] However, the light output should remain stable during all activations, with no decrease as the battery discharges, and the equipment should indicate when to recharge the battery.[11] According to Pereira and others,[13] low battery levels of LED curing lights can influence some properties of composite resins, but is not well known if the irradiance will decrease after a clinically relevant number of light exposures.

Besides the technical achievements of light-curing units, the exterior design of the tip and the light beam size are also important factors for efficient resin polymerization. The external design of the tip should allow the tip to reach posterior regions both as close as possible and parallel to the restored tooth.[4,14,15] An angle, a space between the light-curing tip and the tooth to be restored, any operator error, or movement of the light tip reduces the amount of light and energy delivered to the resin composite restoration.[9]

The objective of this study was to evaluate the light output from six contemporary LED dental curing lights after 25 light exposures each lasting 10 seconds without recharging the battery. In addition, the depth of penetration and accessibility in the mouth were analyzed. The null hypotheses were that 1) the 25 repetitions would not deliver the same irradiance for all six lights, 2) the single peak lights tested would not have the same spectral peak, and 3) the multiple peak (Polywave) lights would not have the same spectral peaks.

METHODS AND MATERIALS

Light-Curing Units on the MARC-Patient Simulator System

The six light-curing units were chosen to represent a wide variety of contemporary LED curing lights (Table 1). Both the exterior and the interior tip diameters were measured using digital calipers (Mitutoyo Co., Kanagawa, Japan). An image was obtained of the tip of each light curing unit (Nikon D5100, Nikon Corp, Tokyo, Japan), and a second image was obtained with a ruler to add the scale at the final image (combining all tip lights in one figure at the same scale). All lights were attached to a rigid stand with the light tip parallel to the MARC patient simulator (MARC-PS, BlueLight Analytics Inc, Halifax, NS, Canada) anterior sensor, shown in Figure 1. The 4-mm-diameter light sensor used in the MARC-PS was located between two maxillary central incisors. The manufacturers of the LED curing lights, serial numbers, and the classification are described in Table 1.

Table 1: *Manufacturer, Serial Number, Light-Emitting Diode (LED) Classification, and Power Source of Light-Curing Units*

Light-Curing Unit	Manufacturer	Serial Number	LED Classification	Power Resource
Bluephase Style	Ivoclar Vivadent AG, Schaan, Liechtenstein	1100000611	Multiple peak	Rechargeable battery (Lipo, 3.7 V 600 mAh)
ESPE cordless	3M ESPE, Sumaré, SP, Brazil	0879857109	Single peak	Rechargeable battery (Li-ion, 3.7 V 2200 mAh)
Elipar S10	3M ESPE, St Paul, MN, USA	939112007892	Single peak	Rechargeable battery (Li-ion, 3.7 V 2300 mAh)
Demi Ultra	Kerr Corporation, Orange, CA, USA	786019408	Single peak	U-40 Ultracapacitor
Valo Cordless	Ultradent Products Inc, South Jordan, UT, USA	C26561	Multiple peak	Rechargeable battery (Life PO4, 3.2 V 750 mAh)
Radii-Cal	SDI Limited, Victoria, Australia	4-18944	Single peak	Rechargeable battery (Li-ion, 7.4 V 1550 mAh).

Determination of Irradiance, Total Energy, and Changes in Irradiance After 25 Exposures

The MARC-PS uses a fiber-optic spectroradiometer (USB 4000, Ocean Optics, Dunedin, FL, USA) to measure the irradiance, the radiant exposure, and the emission spectrum received by simulated cavity preparations in a dental mannequin head. After the lights had been set up the MARC-PS, they were activated for 25 consecutive light exposures each lasting 10 seconds with a fully charged battery or ultracapacitor. The lights were then recharged at the end of the 25th exposure, and the procedure was repeated two more times (n=3, determined by the low standard deviation), always fully charging the battery after the 25th exposure.

All lights were randomly tested. Since Radii-Cal has no 10-second exposure time, a portable digital timer (Herweg, Timbó, SC, Brazil) was used to stop the exposure as close as possible to 10 seconds. The number of exposures was chosen based on the maximum number of exposures that the ultracapacitor of Demi Ultra could deliver in one charge. This study also simulated consecutive light exposures that could be delivered in cases where six metal-free crowns are cemented and where four 10-second exposures on each tooth surface (buccal, occlusal, lingual, mesial, and distal) are recommended, giving a total of 24 exposures. Moreover, 25 exposures of 10 seconds are easily reached by practitioners in dental offices in several procedures, such as multiple direct resin composite restorations. The first and the last exposures (25th) obtained for all light-curing units were tested for the normality of data (Kolmogorov-Smirnov) and compared by paired two-tailed t test (α=0.05).

Determination of the Incidence Angle and Depth of Penetration

A transparent plastic box was filled with red-stained water (rhodamine B, Sigma-Aldrich, St. Louis, MO, USA). All light-curing units were fixed to a retort stand, turned on at same time, with the tip inside the inked water. An image was obtained of the light dispersion with a camera. A second image was obtained with a ruler beside the light tip to add the scale to the final image. Although the refractive index of stained water is different from the refractive index of the air and the composites this methodology was performed to visually observe the differences in the light beam spread from the lights.

Tip Accessibility in Posterior Region

The maximum mouth opening was fixed to 35 mm at the incisors in a dental mannequin (Marília Dental Mannequin, Marília, SP, Brazil), to represent an average mouth opening.[16] The mannequin and the camera (Nikon D5100, Nikon Corp, Tokyo, Japan) were fixed in the same position (and distance) for all the images. The ability to reach the lower second molar with the tip parallel to the occlusal surface of this tooth was determined, and for those lights unable to fulfill this parameter, a second picture was

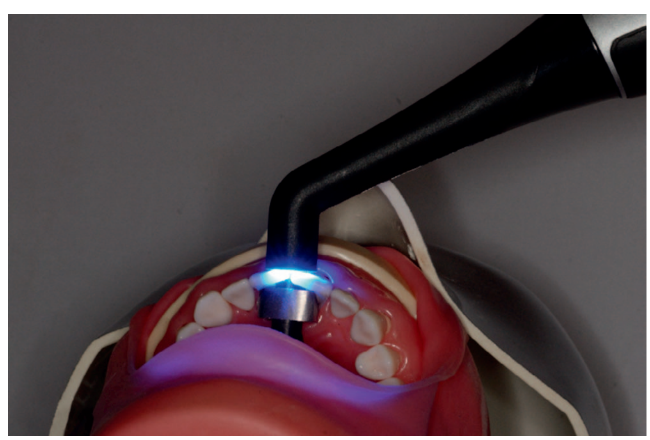


Figure 1. *Light-curing tip parallel to the MARC-PS anterior sensor.*

Table 2: *External and Internal Tip Diameter (mm) of Light-Curing Units*

	Bluephase Style	ESPE Cordless	Elipar S10	Demi Ultra	Valo Cordless	Radii-Cal
External	9.73	7.96	9.79	10.57	13.10	11.65
Internal	8.62	6.77	8.81	7.83	9.40	6.92

taken with the tip parallel to the most distant tooth possible.

RESULTS

Light-Curing Units and Tip Size

The external and internal dimensions of the light tip and the characteristics of the light-curing tips are showed in Table 2 and Figure 2, respectively. The small tip diameters, found for ESPE Cordless and Radii-Cal, may not cover an entire cavity preparation in a molar class II that is greater than 7 mm in mesiodistal width; thus, overlapping exposures are necessary to cover all of the resin composite restoration. Figures 2A to 2C show that the light source is not always close to the tip. In contrast, the LED emitters can be seen at the tip ends of the Demi Ultra, Valo Cordless, and Radii-Cal (Figures 2D, 2E, and 2F, respectively).

Determination of Irradiance, Total Energy, and Changes in Irradiance After 25 Exposures

The mean irradiance, radiant exposure (first and 25th), and wavelength emission peaks are shown in Table 3. After collecting the data using the MARC-PS, the results were plotted with GraphPad Prism 6 (GraphPad Software, Inc., La Jolla, CA, USA). Figure 3 shows the wavelength of single peaks (Figure 3A) and multiple peak lights (Figure 3B), and the irradiance for all six lights (Figure 3C). The single peak lights delivered different spectral peak and irradiance. Multiple peak lights also had different spectral peaks and irradiance. The Demi Ultra delivered a pulsed light output (Figure 3C) and the mean irradiance was determined by the average of the high and low pulse values. Radii-Cal did not emit a stable irradiance compared with the other lights tested, as shown by the irregularities in the irradiance curve (irradiance/time).

After 25 exposures, the data were combined and are reported in Figure 4. All six lights delivered a relatively stable irradiance for the 25 exposures (Figure 4A,B). The difference in irradiance between the first and the last exposure is shown in Figure 4C and D. Depending on the light-curing unit, there was a small decrease ranging from 1.9% to 8.4% in the irradiance for all six lights; however, for the ESPE Cordless, Valo Cordless, and Radii-Cal there was a statistical difference between the first and the last exposure (p=0.0086, p=0.0103, and p=0.0118, re-

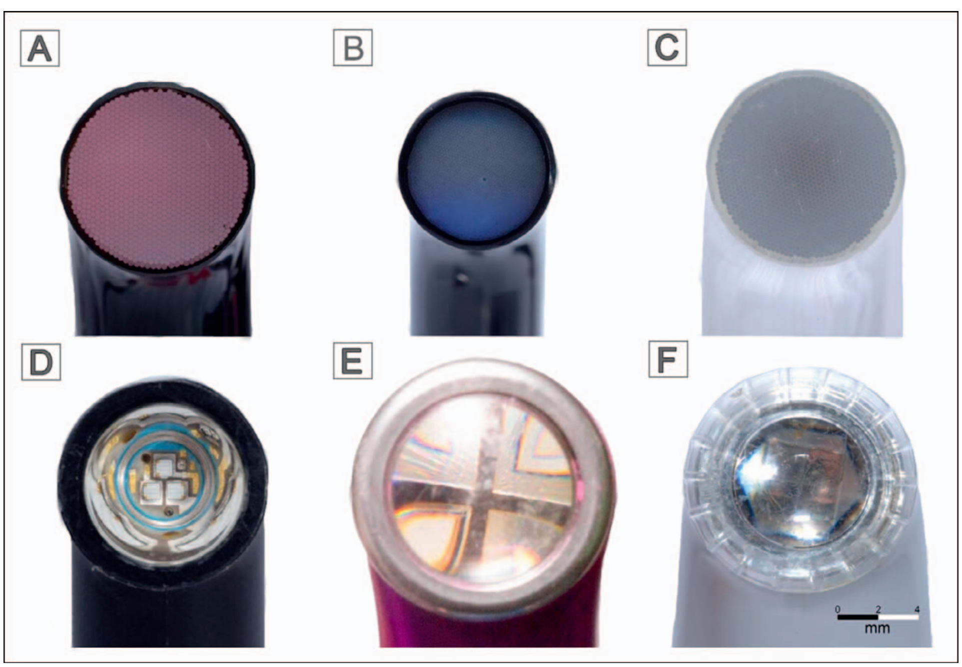


Figure 2. *LED light-curing tips. (A): Bluephase Style. (B): ESPE Cordless. (C): Elipar S10. (D): Demi Ultra. (E): Valo Cordless. (F): Radii-Cal. Note the different tip diameters (all tips imaged to the same mm scale).*

Table 3: *Mean (Standard Deviation) of Irradiance and Radiant Exposure, and Spectral Emission Peak of Light-Curing Units*[a]

	Mean Irradiance, mW/cm^2	First Radiant Exposure, J/cm^2	25th Radiant Exposure, J/cm^2	Mean Decrease, %	Emission Peak, nm
Bluephase Style	1036.1 (31.6)	11.2 (0.4)a	10.5 (0.1)a	6.1	410
					458
ESPE Cordless	1579.6 (74.5)	15.9 (0.7)a	14.5 (0.5)b	8.4	460
Elipar S10	1840.7 (46.2)	18.9 (0.5)a	18.5 (0.4)a	1.9	458
Demi Ultra	1607.9 (5.3)	16.3 (0.2)a	15.8 (0.5)a	3.3	462
Valo Cordless	1474.2 (35.8)	15.1 (0.5)a	14.6 (0.3)b	3.2	400
					450
					460
Radii-Cal	839.6 (61.2)	8.5 (0.7) a	7.9 (0.9)b	7.2	454

[a] *Different letters show significant difference between the first and the 25th exposures ($p<0.05$).*

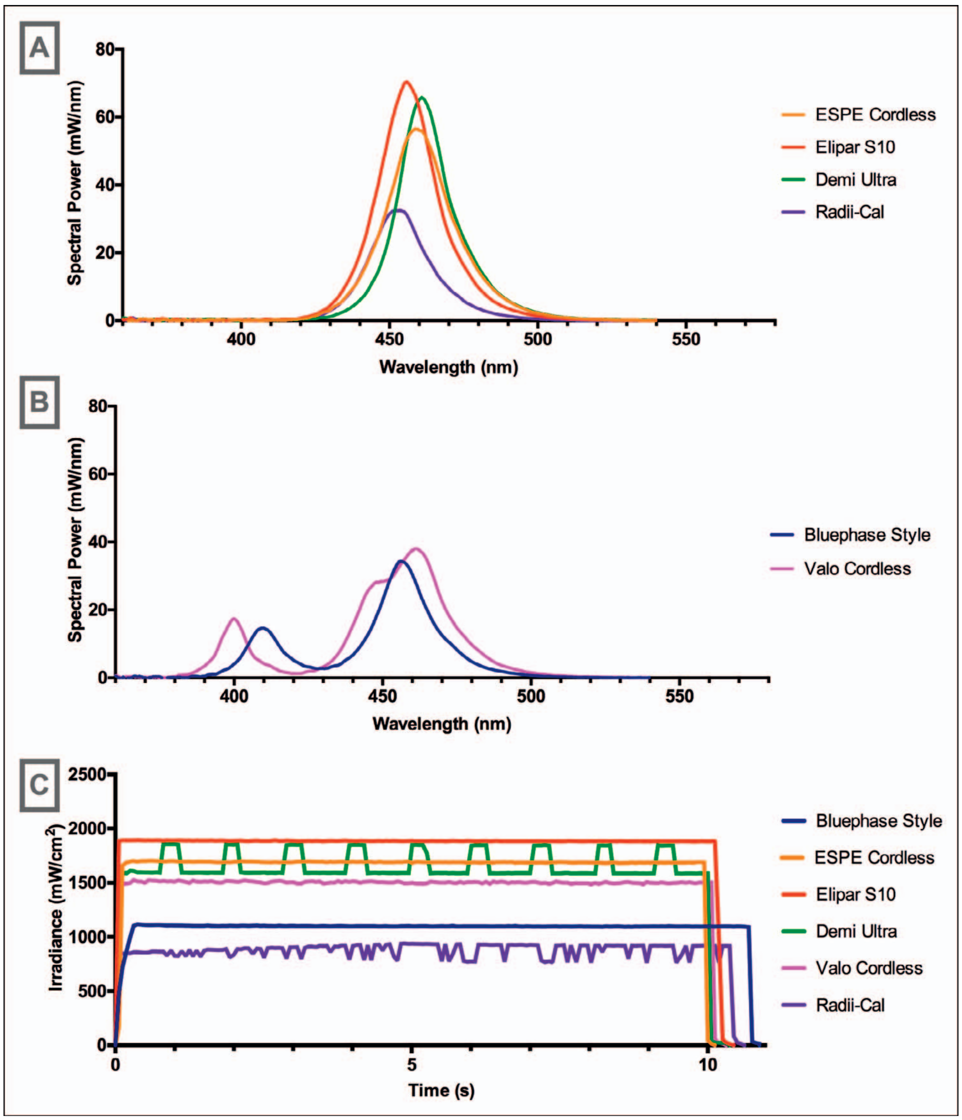


Figure 3. *Spectral radiant power output (mW/nm) and irradiance (mW/cm^2) from six curing-light units. (A): Emission spectrum from single peak lights. (B): Emission spectrum from multiple peak lights. (C): Irradiance delivered at the tip of all six lights.*

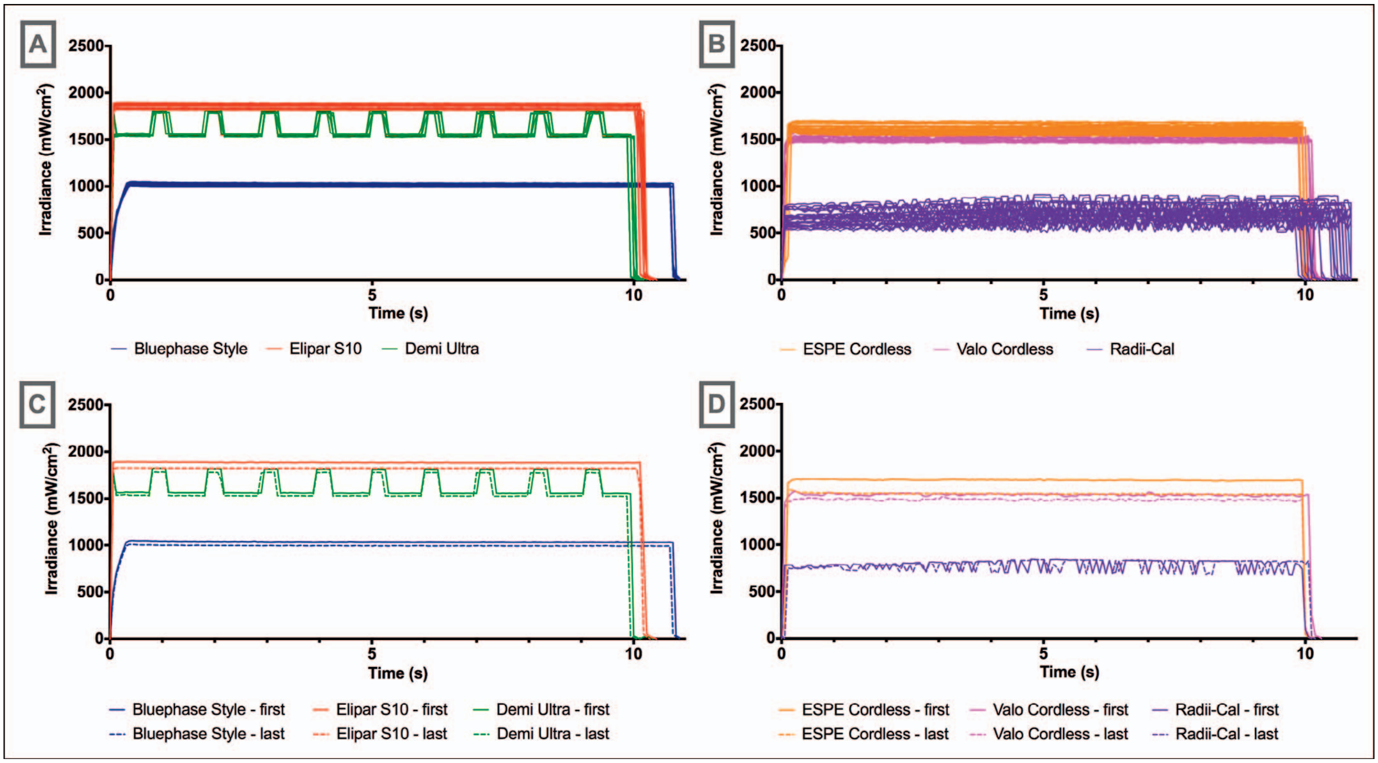


Figure 4. *Irradiance at the light tip of the curing-light units. (A, B): Twenty-five exposures of 10 seconds. (C, D): The first (solid lines) and the last exposure (dotted lines) of each light.*

spectively). The ESPE Cordless showed the largest decrease (8.4%) when the last exposure was numerically compared to the first exposure, whereas there was a 3.2% decrease for the Valo Cordless light.

Radii-Cal delivered the lowest irradiance and radiant exposure numerically compared with the other LED light-curing units tested. For this light-curing unit, a 10-second exposure was obtained manually with the help of a portable digital timer, so the time of each exposure was not exactly the same (Figure 4B). However, using the average irradiance delivered, the radiant exposure that would be delivered in 10 seconds was calculated.

Determination of Light Beam Spread

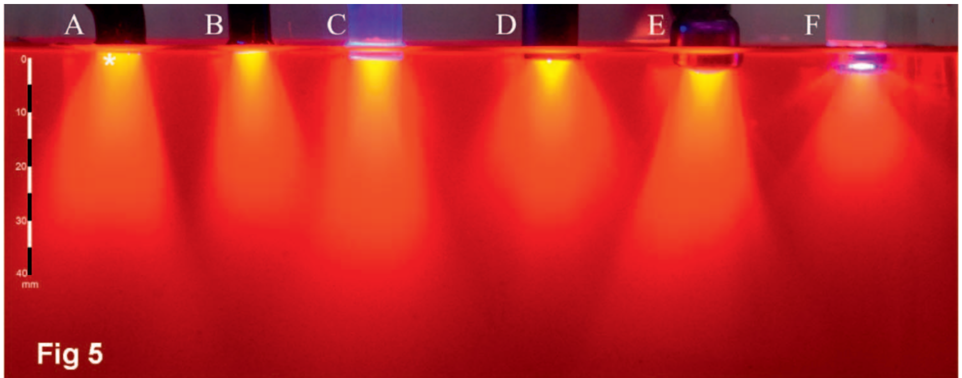
An image of the light beam spread through the red water of all six curing light units is shown in Figure 5. Light-curing units with higher radiant exposure (Table 3) delivered a deeper brighter area (*) compared with Radii-Cal (Figure 5F). The brighter regions may be related to the irradiance received and the amount of energy delivered from the light to a resin composite. When compared on the same scale, the light-curing units from A to E showed a brighter area that was 7-mm to 10-mm length and light-curing unit F (Radii-Cal) only 3 mm. Likewise, the depth of light penetration in the red water ranged from 26 mm to 30 mm (Figure 5A to E) and Radii-Cal was only 21 mm. In addition, it is possible to observe differences in the light dispersion and the region where the restoration would be irradiated.

Tip Accessibility in the Posterior Region

The ability to align the light tip parallel to the tooth is shown in Figure 6. The Valo Cordless and Bluephase Style (Figure 6A, F) were able to reach the second molar with the tip parallel to the tooth (occlusal exposure). At the 35 mm interincisal opening, the Radii-Cal was unable to reach any posterior tooth with the light tip parallel to the occlusal surface (Figure 6E). Figures 6A to 6F show the most posterior location where each tip can reach, yet still keep the light tip parallel to the occlusal surface. Figures 6G to 6J show the inclination of the light tip that would occur when polymerizing an occlusal restoration in the second molar region at an interincisal opening of 35 mm.

DISCUSSION

Light-cured resin composites have become the material of choice for direct restorations and are widely used in dental practice.[17] In 2012, it was



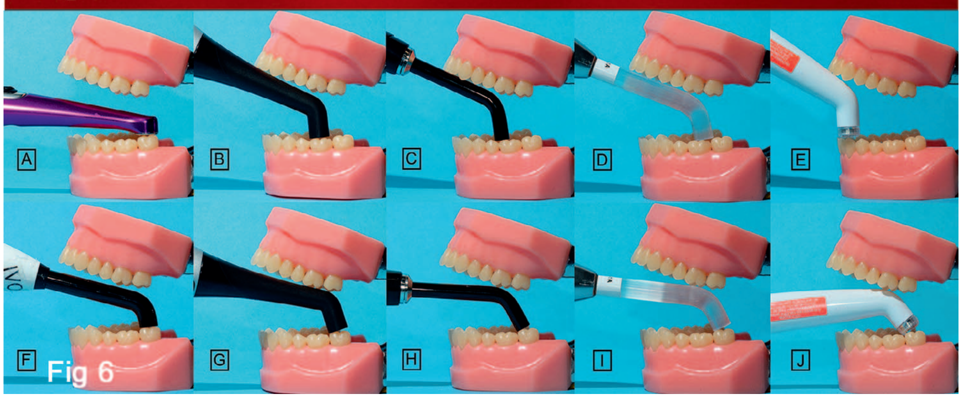


Figure 5. *Beam spread of curing-light units. (A): Bluephase Style. (B): ESPE Cordless. (C): Elipar S10. (D): Demi Ultra. (E): Valo Cordless. (F): Radii-Cal. *Brighter area, ie, the irradiance delivered to a restoration.*

Figure 6. *Ability of six light-curing units to reach the mandibular second molar. (A): Valo Cordless. (B, G): Demi Ultra. (C, H): ESPE Cordless. (D, I): Elipar S10. (E, J): Radii-Cal. (F): Bluephase Style. (A–F): Accessibility limit. (G–J): Angulation of the light tip required to access the second molar.*

stated that more than 260 million direct RBC dental restorations are placed annually worldwide,[18] and this number will only increase as the use of dental amalgam is phased down and becomes less frequent.[19] For many years, halogen light-curing units were used; however, LED curing units have now become the most popular curing lights. The irradiance delivered by a light-curing unit is calculated from the radiant power incident on a surface of known area, and unless a sufficient number of photons are received at the appropriate wavelengths, the polymerization of the RBC can be inadequate.[20] In this study, the irradiance decreased slightly after 25 exposures of 10 seconds each, accepting the first null hypothesis that the 25 repetitions would not deliver the same irradiance for all six lights.

All the lights tested delivered a very stable irradiance during each exposure, suggesting that the battery charge had minimal influence on irradiance after 25 exposures of 10 seconds. However, the Radii-Cal did not show a homogeneous irradiance for all exposures and presented the lowest irradiance and radiant exposure numerically compared with the other curing lights tested. Higher temperatures generally reduce the output from LED emitters and have a negative influence on both the reliability and durability of the LED chip. The increase in temperature can also change the LED peak wavelength.[21] For all lights, the decrease in irradiance and energy was not large; however, it is suggested to recharge the battery often and let the light cool down between multiple uses. Allowing the cooling of LED lights may minimize the small changes in irradiance and increase the durability of the light. Demi Ultra uses an ultracapacitor as an energy source, and the advantage of this is the reduction in the time required to fully charge the unit. In this study, it took only about 40 seconds to fully recharge the Demi Ultra.

Resin photopolymerization can be affected by differences in the spectral emission of light-curing units.[4,5,22] Different spectral emission peaks were found for single peak lights, accepting the second null hypothesis stating that all single peak lights would not have the same emission peak. Also, the multiple peaks lights had different spectral emission peaks, accepting the third null hypothesis for the same reason. Camphorquinone is the most commonly used photoinitiator in dental polymers.[6,23] The maximum absorbance peak of camphorquinone is at 470 nm, but is activated in a range from 400 to 500 nm,[24] and it is also activated by light of wavelengths below 320 nm.[25] All of the single peak lights and multiple peak lights tested in this study deliver a spectral emission that is compatible with the camphorquinone absorbance range. The Radii-Cal delivered the lowest spectral power numerically compared to the other single peak lights tested.

Alternative photoinitiators, such as PPD, Lucerin TPO, BAPO (Irgacure 819), and Ivocerin, are also found in the wide range of dental polymers available on the market.[6,26] TPO is very sensitive to light below 420 nm,[26] PPD below 460 nm, and BAPO below 440 nm.[24] Ivocerin is a photoinitiator under patent protection, and according to the manufacturer (Ivoclar Vivadent, Schaan, Liechtenstein), it is very sensitive to light below 450 nm, with an absorbance peak close to 410 nm. Because of their relatively narrow emission spectra, all four single peak lights tested in this study cannot activate the TPO initiator, that is used in Tetric EvoCeram (Ivoclar Vivadent) and Vit-l-escence (Ultradent Products Inc, South Jordan, UT, USA) composites.[27] However, the multiple peak lights, such as Valo and Bluephase Style should be able to activate the alternative photoinitiators.

Resin composite materials require different radiant exposure levels,[28] and the practitioner should be aware of the radiant exposure or the exposure time and the irradiance recommended by the manufacturer of each material. The shade of the composite, thickness of the increment, and distance from the light source should be taken into account regarding the required exposure time and the radiant exposure required to adequately polymerize the resin.[9] However, the practitioner should not arbitrarily increase the time of exposure, but instead they should follow the exposure time/irradiance according to the resin composite manufacturer's recommendations for each resin shade. Otherwise, the practitioner may deliver too much energy and cause an unacceptable temperature increase in the pulpal or soft tissues.[9,29,30]

Besides the technical guidance of light-curing units described in this study, to achieve optimal polymerization, dentists should (1) take in account the size and external design of the tip, (2) place the light directly on the composite restoration at 90° perpendicular to the surface, and (3) almost in contact with restorative material.[31] According to Konerding and others, a tilted light tip will reduce energy delivery and may impair the polymerization.[14,31] Excessive tip inclination will decrease the radiant exposure received by the resin. The Valo Cordless and Bluephase Style were able to reach the second molar occlusal with the tip parallel to the occlusal surface of the tooth. Figure 5 represents an easy method for practitioners to understand how the light beam spreads from light-curing units and by examining the brighter area and depth of penetration, may be used to compare curing lights. The light with least irradiance produced the least bright area and the lowest depth of penetration compared to the other lights. Another concern regarding the curing light is the tip diameter. The practitioner should be aware that the internal diameter from where the light is emitted should cover the full width of a large restoration.[5] Lights such as the ESPE Cordless and Radii-Cal may require multiple exposures to cover the full width of a molar class II cavity preparation. Otherwise, at the proximal box, inadequate polymerization may cause premature failure of class II composite resins at the gingival margin.[32]

Excessive light tip inclination can decrease the radiant exposure received by the resin, and the percentage of decrease is dependent on the light-curing unit. However, even lights with high irradiance values will experience a significant decrease in radiant exposure as the tilt angle increases.[31] In addition to correctly positioning the light tip over the RBC, it is important that the practitioner watch what he or she is doing when light curing through a blue-blocking filter to protect their eyes.[15,33]

CONCLUSION

Within the limitations of the current study, the following conclusions can be made:

1. Not all light-curing units deliver the same quality (wavelength) and quantity (radiant exposure) of blue light in 10 s. Practitioners should match the light-curing unit with the wavelengths required by the photoinitiators used in the restorative materials they are using.
2. Practitioners should be aware that after several exposures in a row (25 times), the radiant exposure may decrease between 2% and 8%.
3. The light-curing unit should be designed to allow the light tip to be brought parallel to and as close as possible so that the light is delivered at 90° perpendicular to the surface of the restoration.

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Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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