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The light-curing unit: An essential piece of dental equipment

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Introduction: This article describes the features that should be considered when describing, purchasing and using a light-curing unit (LCU). **Methods:** The International System of Units (S.I.) terms of radiant power or radiant flux (mW), spectral radiant power (mW/nm), radiant exitance or tip irradiance (mW/cm^2), and the irradiance received at the surface (also in mW/cm^2) are used to describe the output from LCU. The concept of using an irradiance beam profile to map the radiant exposure (J/cm^2) from the LCU is introduced. **Results:** Even small changes in the active tip diameter of the LCU will have a large effect on the radiant exitance. The emission spectra and the effects of distance on the irradiance delivered are not the same from all LCUs. The beam profile images show that using a single averaged irradiance value to describe the LCU can be very misleading. Some LCUs have 'hot spots' of high radiant exitance that far exceed the current ISO 10650 standard. Such inhomogeneity may cure the resin unevenly and may also be dangerous to soft tissues. Recommendations are made that will help the dentist when purchasing and then safely using the LCU. **Conclusions:** Dental manufacturers should report the radiant power from their LCU, the spectral radiant power, information about the compatibility of the emission spectrum from the LCU with the photoinitiators used, the active optical tip diameter, the radiant exitance, the effect of distance from the tip on the irradiance delivered, and the irradiance beam profile from the LCU.

Key words: *Dental curing lights, light measurement techniques, beam profiling, fibre optic spectrometer, resin-based composites, light and optics terminology, radiant exposure*

INTRODUCTION

The FDI World Dental Federation represents over one million dentists, most of whom will own and use a dental light-curing unit (LCU). This LCU and how it is used will affect the physical properties, biocompatibility and the clinical success of light-cured dental polymer systems (resin-based composites, adhesives, orthodontic resins, luting agents, sealants, etc.) that are used in the dental office[1–3]. Of note, globally, there exists a large discrepancy between how long resin composite restorations are reported to last in well-controlled clinical trials[4,5], and how long they last when placed in most dental offices[6–9]. Although the reasons for these discrepancies in the long-term success of restorations are multifactorial, the general lack of understanding about the differences between LCUs, how to describe the output from the LCU, and how to use the LCU in everyday dentistry[10–19] may very well be contributing factors. Due to this lack of knowledge and information about the LCU and the consequences of inadequate light curing, the dentist may not use the LCU correctly, and they may purchase an inexpensive device from the Internet, thinking that all LCUs emit similar blue light and will have equivalent efficacy. This can result in the dentist unknowingly delivering less overall energy or the wrong wavelengths of light to photocure the resin in the mouth in comparison to the energy delivered in the vast majority of laboratory studies and in well-controlled clinical trials. After reading this article, the reader will know what to look for when purchasing and using a curing light. They will understand reasons why there can be considerable differences between LCUs, and why reliance upon a single reported irradiance value can be misleading.

Light-curing units

Small, battery-operated and energy-efficient light-emitting diode (LED) curing lights dominate the market[10,14,18,20]. The LCUs in *Figure 1* offer different features but, unfortunately, the cost of the unit and a 'high' irradiance value greater than 1,000 mW/cm^2 are the two main factors upon which many clinicians base their decision when purchasing a new LCU. However, there are considerable differences in the light output from almost all currently available LCUs that cannot be adequately described by an irradiance value alone[21]. Because most dentists were never taught what to look for when purchasing their next LCU, or how to use the LCU correctly, a meeting attended by over 50 key opinion leaders and manufacturers was held in 2014. At the conclusion, a consensus was achieved on what the clinician should look for when purchasing and using a new curing light[22–24]. These recommendations are freely available to download[22,23].

Curing lights are medical devices

In most countries, dental LCUs are classified as medical devices, and it behooves the dentist to ensure that any medical device they use has been 'cleared' or 'approved' for use on patients[25–27]. Indicators that a curing light should not be used on patients, or that the safety of the electrical components in the LCU and its charger, has not been verified, would be the lack of appropriate certification labels, poorly worded instructions for use, the lack of contact information should any harm or malfunction occur, or that the device is not listed as being cleared or approved on the regulatory authority database.

Figure 1. An assortment of light-emitting diode (LED) curing lights. Note the range of shapes and sizes.

Describing the light-curing unit

Most manufacturers and researchers alike do not describe the light output from the LCUs in a consistent manner[21,28]. This has led to the unintentional dissemination of misinformation about the light sources[21], or about the photo-curing requirements of light-cured dental polymer systems[28–30]. Because the output from the LCU, the radiant exposure, and the wavelengths (nm) of light received by the light-cured dental polymer systems used in the vast majority of studies have often not been adequately reported[28], clinical decisions based on the results and conclusions from these studies may not be valid.

To ensure that all parties are describing the light from the LCU using the same terms, the International System of Units (S.I.) should be used by manufacturers, researchers and clinicians alike (*Table 1*). While the current ISO 10650 standard[31] provides much useful and important information, it is based on the assumption that the light output is homogeneously distributed across the light tip. This is not the case in many dental LCUs[21,32–37]. In the standard[31], the total radiant power (mW) is measured from the LCU and then divided by the optical cross-sectional area of the light guide/light-emitting tip to produce a single averaged radiant exitance value in mW/cm^2. This radiant exitance at the light tip is the same as the irradiance (also in mW/cm^2) at the light tip. The standard[31] also requires that the radiant exitance in the 380–515 nm wavelength region should not be greater than 4,000 mW/cm^2.

Relationship between radiant power (radiant flux), active light-emitting area and radiant exitance (tip irradiance)

The use of budget priced LCUs that have often been purchased over the Internet is becoming popular[16]. Many of these budget LCUs appear to be equivalent to higher cost LCUs from quality manufacturers because these budget lights often claim similar radiant exitance (irradiance) values. However, the light output from these budget lights is often unstable and sometimes declines rapidly as the battery discharges[38–41]. In addition, most budget LCUs have only a small 6- or 7-mm diameter 'active' light tip from where useful light is emitted, whereas most lights from quality manufacturers have a 9–11+ mm active tip diameter[42,43]. Because the active area is calculated from the cross-sectional area, πr^2, any reduction in the active tip diameter from where light is emitted will have a substantial effect on the tip area and the radiant exitance. For example, if the active tip diameter is reduced from 10 to 7 mm, the area from where light is emitted is halved from 78.6 mm^2 to 38.5 mm^2.

Table 1 Glossary of S.I. radiometric terms used to describe the output from dental light curing units (LCUs)[21,29]

Term	Unit commonly used in dentistry	Symbol	Explanation
Radiant energy	Joule	J	This is the energy emitted from the LCU
Radiant power (or radiant flux)	Watt	W or J/second	This is the energy per unit of time emitted from the LCU
Radiant exposure	Joule per square centimetre	J/cm^2	This is the energy received from the LCU per unit area
Radiant exitance, tip irradiance, or radiant emittance	milliWatts per square centimetre	mW/cm^2	This is the radiant power from a defined unit area. The radiant exitance is the same as the tip irradiance from the LCU at zero distance
Irradiance (incident irradiance)	milliWatts per square centimetre	mW/cm^2	This is the radiant power received by a unit area. It reflects an average value received over a defined area.
Emission spectrum	nanometres	Nm	These are the wavelengths of the light emitted from the LCU
Spectral radiant power	milliWatts per nanometre	mW/nm	This is the radiant power at a specific nm wavelength delivered from the LCU
Spectral irradiance	milliWatts per square centimetre per nanometre	mW/ cm^2/nm	This is the irradiance received by a defined area at each nm of light emitted from the LCU

This will double the radiant exitance. Consequently, without increasing the radiant power output from the LCU, a manufacturer can increase the radiant exitance (irradiance) by reducing the tip area. For this reason, comparing LCUs using the radiant exitance (tip irradiance) value alone without also knowing the radiant power from the LCU and the active optical tip diameter or the active tip area should be avoided[21].

Effect of distance from the light tip

As the distance from the light tip increases, the irradiance received declines[2,44–46]. The effect of distance is not the same for all LCUs. This reduction in the irradiance received does not follow the 'inverse-square law' because the light from most LCUs is a somewhat focused beam of light. Some LCUs emit a well-collimated beam of light and, for others, the beam spreads out rapidly. Thus, manufacturers should report the radiant exitance not only at the light tip, (tip irradiance), but also the irradiance delivered at clinically relevant distances up to 10 mm away.

Emission spectrum

Dentists can now purchase light-cured resin systems that use a variety of alternative photoinitiators in addition to or as replacements for camphorquinone (CQ), and they can also buy LCUs that emit different emission spectra of light[1,2,21]. The CQ initiator that is used in almost all dental resins is most efficiently activated by blue light at 468 nm. However, CQ is yellow, and some manufacturers use several other photoinitiators that are less yellow and are more efficient than CQ. These initiators are usually most sensitive to ultraviolet or violet light between 380 and 410 nm[1,2,47,48].

In contrast to quartz-tungsten-halogen (QTH) curing lights that emitted a broad spectrum of both violet and blue light (*Figure 2a*), the LED emitter used in many contemporary LCUs can only produce light over a limited spectral range (*Figure 2b*). Thus, single-peak LED curing lights that deliver very little light below 420 nm are not ideal LCUs to activate the initiators that require violet light[1,2,21]. However, the differences between the resin-based products or between LCUs are not readily apparent to the purchaser because all LCUs will activate the CQ initiator that is used in almost all resin-based products and the top surface of the resin will feel hard. Consequently, the dentist may not realise that their LCU does not deliver light below 420 nm and thus cannot activate the additional photoinitiators.

To better activate these alternative photoinitiators, some LED curing lights (*Figure 2c,d*) now include additional LED emitters that produce additional light in the violet range of wavelengths[2,20,21,32,36]. *Figure 2 (c,d)* illustrates that the number and location of these violet and blue light emission peaks can vary between manufacturers, as does the relative contribution of each wavelength peak to the total radiant power output from the LCU. However, unless the LCU is carefully designed, the addition of several different wavelength LED emitters in the LCU can negatively affect the total amount of blue light present and the overall uniformity of the emitted light beam. This will then change the spectral irradiance received across the resin surface, which may then produce an uneven polymerisation within the RBC[2,21,32,36,49,50].

Light beam irradiance uniformity

Beam profiling using a digital camera is used to examine the uniformity of light beams[51,52]. The beam-profiling software can produce both two-dimensional and three-dimensional images of the radiant exitance

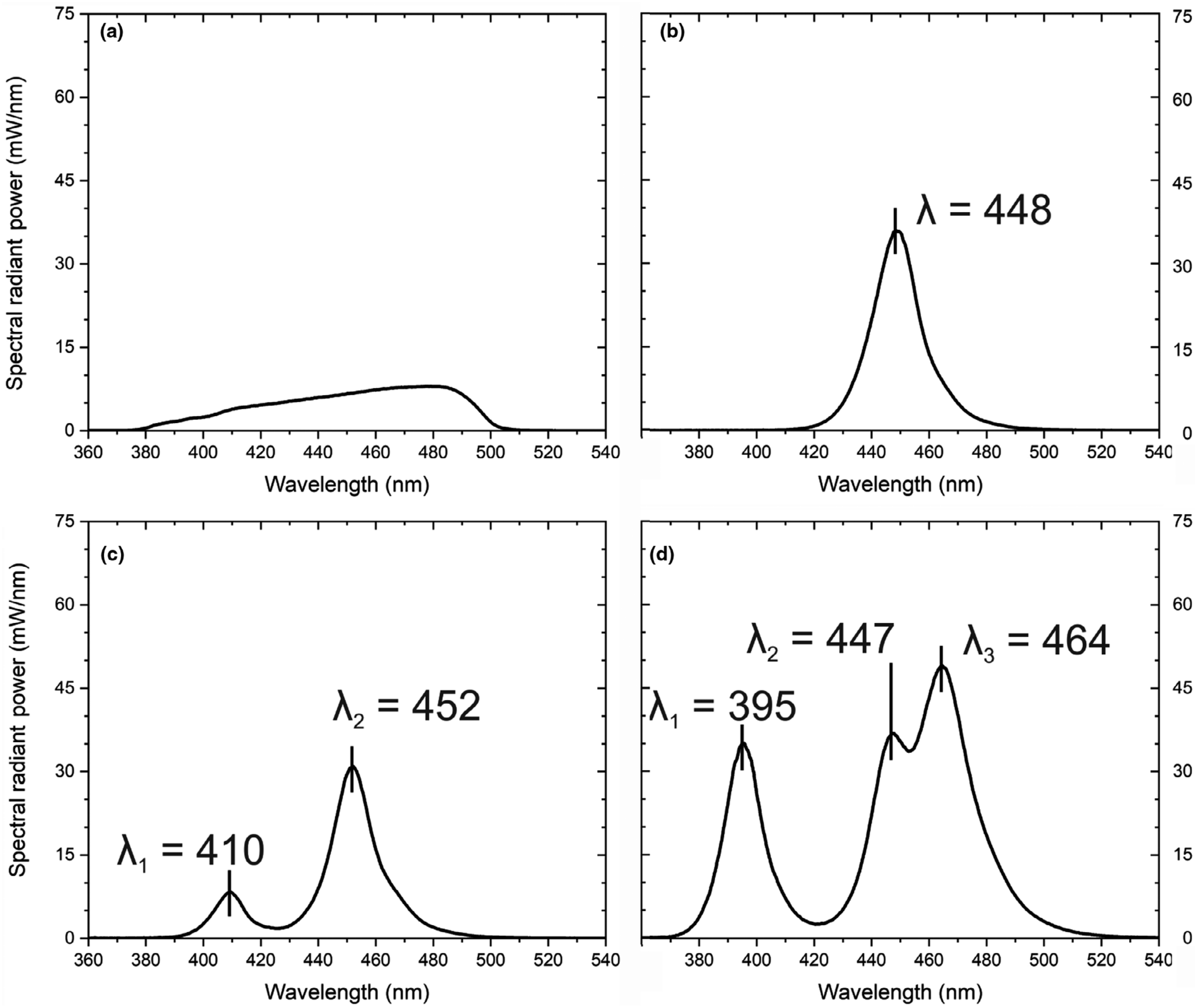

Figure 2. Emission spectra (nm) from (a) a quartz-tungsten-halogen (QTH), (b) a single-peak light-emitting diode (LED), (c) a dual-peak, and (d) a multi-peak LED curing light. To the human observer, the light-curing units (LCUs) will appear to emit similar 'blue' light.

across the tip of the light source as well as numerical data about the light source[51,52]. The two images in *Figure 3* illustrate the difference between the single averaged irradiance value provided by the ISO 10650 standard[31] and the information provided by a beam profile from the same LCU. In *Figure 3(a)*, the radiant power was divided by the optical tip area to produce an averaged radiant exitance of 1,822 mW/cm^2. The image captured by the beam profile camera in *Figure 3(b)* shows why this information can be misleading. Although the average radiant exitance is still 1,822 mW/cm^2, there are four 'hot spots'of high radiant exitance that are above 12,600 mW/cm^2, and other regions where the light output is lower. These four 'hot spots' deliver three times the maximum irradiance of 4,000 mW/cm^2 allowed in the ISO 10650 standard[31]and six times more than the 2,000 mW/cm2 maximum value recommended in the 2014 consensus document[22]

Light beam spectral uniformity

Figure 4 illustrates the beam profile of one dual-wavelength peak LED curing light that has one violet light and two blue LED emitters in the LCU. When the light output at the tip is viewed through blue-light-blocking orange glasses, the output from the one violet and two blue LEDs is visible, and 'hot spots' of high irradiance are also evident. The image clearly shows that the light is not well mixed. When the tip

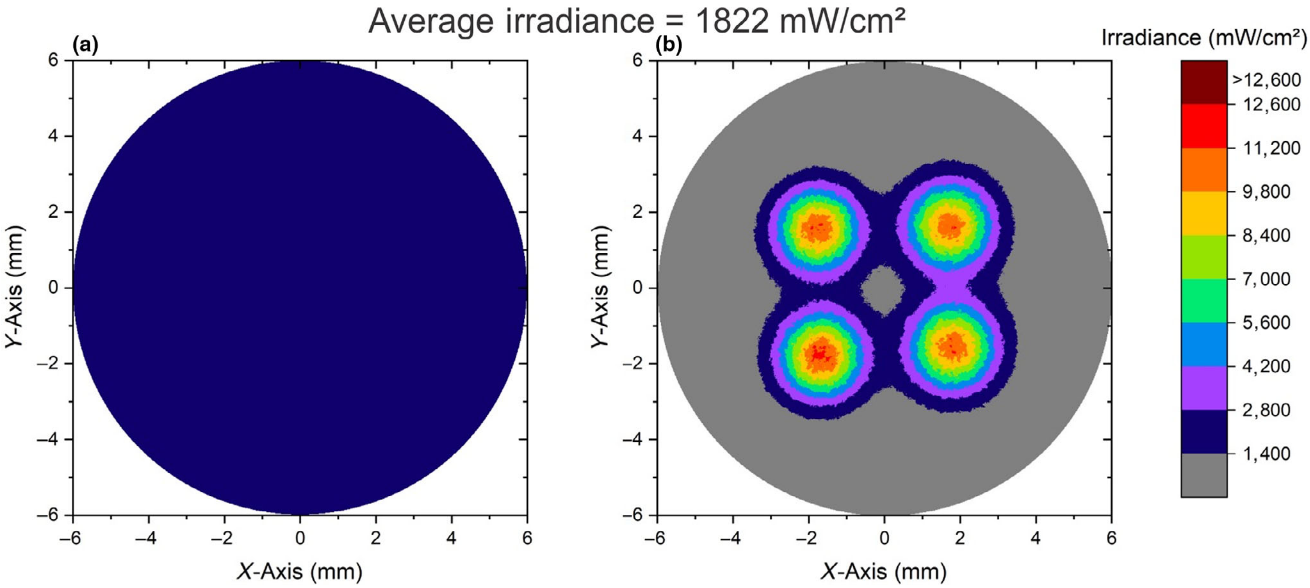

Figure 3. This light-curing unit (LCU) had an averaged radiant exitance of 1,822 mW/cm^2. The figure depicts the anticipated beam profile (a) that was obtained from the quotient of the power and area (as per the ISO 10650 standard). (b) The actual scaled irradiance beam profile of the same LCU showing that although the average radiant exitance is still 1,822 mW/cm^2, there are four 'hot spots' where the radiant exitance is above 12,600 mW/cm^2 surrounded by regions of lower radiant exitance.

irradiance from the same LCU is viewed using a beam profiler camera through narrow bandpass filters that only allow either violet (400 ± 5 nm) or blue (460 ± 5 nm) wavelengths of light through, the spectral uniformity of the light emitted from the LCU in the violet and blue regions becomes quantifiable[33,36,49]. Thus, dentists should look for a good optical design in the LCU that can homogenise the light so that both the irradiance and the emission spectrum are uniformly distributed across the light tip, that is there are no 'hot spots'.

Active diameter of light beam

The beam profile also shows the active diameter of the tip from where light is emitted. This active tip diameter is important because any RBC that is not covered by the active region of the light tip will be less well polymerised[53,54], and most laboratory studies only evaluate the ability of the LCU to polymerise the resin that is directly under the centre 4-mm diameter region, not at the edges[54]. Based on a favourable report, clinicians may then attempt to light cure the entire adhesive layer in mesial-occlusal-distal (MOD) cavities using just one exposure and, if using a bulk-fill resin-composite, they may then also light cure the restoration as a whole using only one light exposure. The clinician may not realise that in order to adequately light cure the entire surface of the cavity preparation or restoration with a single exposure, the active light tip area should completely cover the whole surface. To be practical, an overlap of 1 mm beyond the restoration would be ideal, as this will allow for some small movements at the light tip. Because the active optical diameter of many LCU tips is smaller than a MOD preparation in a molar tooth[14,21,32,42,43,45,55], the likely result will be that the adhesive and the resin at the bottom of the proximal boxes will be inadequately polymerised in just one exposure. Instead, multiple exposures from different locations are required. To illustrate this effect, the beam profiles of two different curing lights, one with an 11.6-mm active optical tip diameter and the other with a 6.6-mm active optical tip diameter, were superimposed over a maxillary central incisor and a mandibular first molar tooth (*Figure 5*). The differences in both the width and uniformity of light coverage over the teeth are striking. However, although a wide tip may appear to be preferred, if the light tip also covers the gingiva, the soft tissues may be burnt if the tip irradiance is too high, or the LCU is used incorrectly[56,57]. Consequently, a narrower tip (6–8 mm in diameter) is indicated for curing small increments of RBC, or Class V restorations that are close to the gingiva.

Radiant exposure uniformity

It has been suggested that each 2-mm-thick increment of RBC should receive approximately 16 J/cm^2 in order to be adequately photo-cured[58]. Consequently, a novel approach using the data acquired from beam

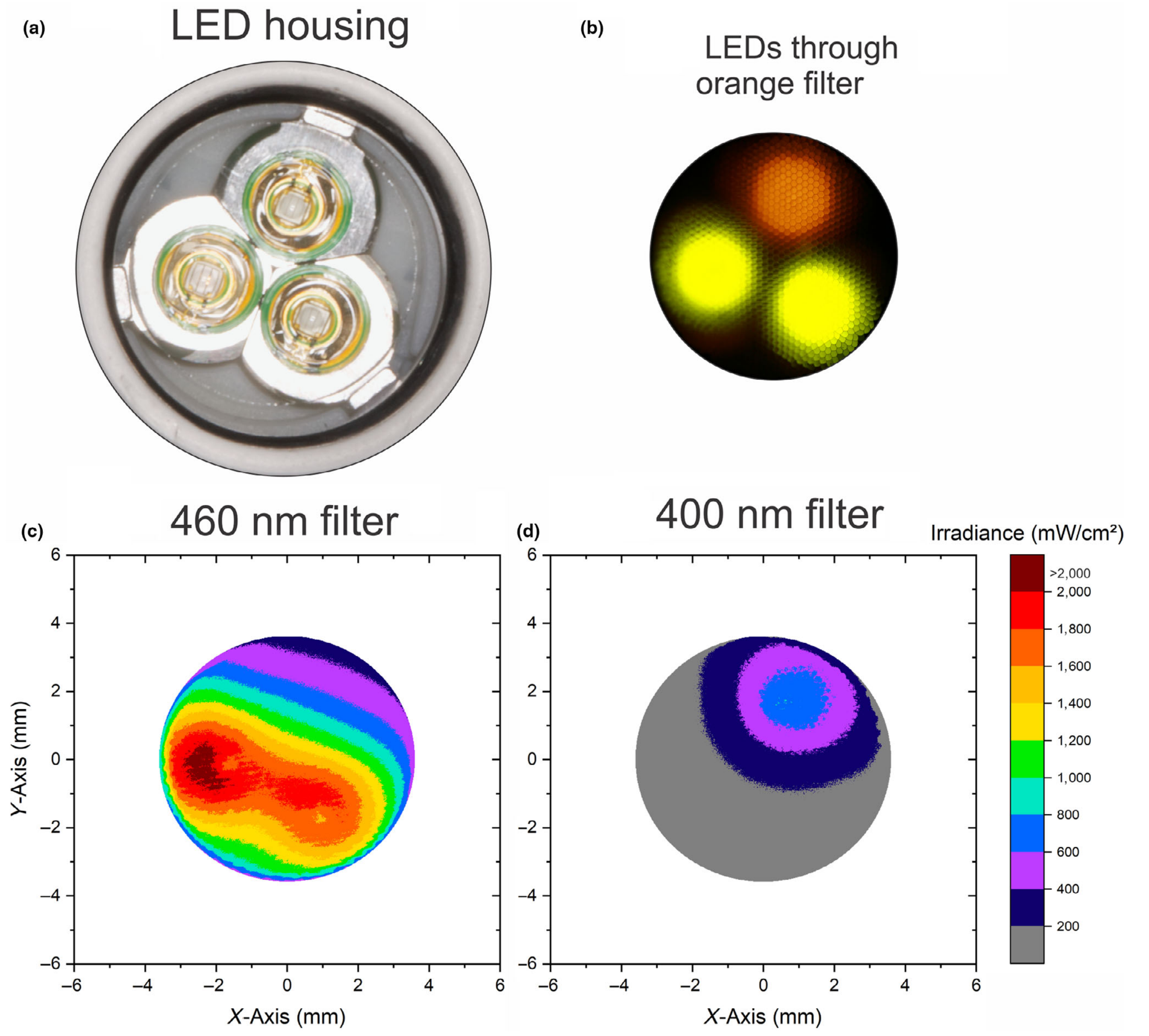

Figure 4. This figure illustrates how the reader can view the light output from a dual-peak light-curing unit (LCU) through orange blue-light-blocking glasses. The distribution of the wavelengths and the tip irradiance are clearly not uniform (b). Instead, they correspond to the location (a) of the two blue and one violet light-emitting diode (LED) emitters in the LCU housing. When the same light is imaged through either (c) a 460 ± 5 nm or (d) a 400 ± 5 nm narrow bandpass filter into a beam profiler camera, the irradiance received in each region can be measured.

profiling is to multiply the irradiance (mW/cm^2) by the exposure time (seconds) to produce a map of the radiant exposure (J/cm^2). When this is done, it can be seen that LCU (a) in *Figure 6* does not deliver a uniform amount of energy across the light tip. Outside of the energy 'hot spot' at the centre, LCU (a) will emit less than 16 J/cm^2 in 20 seconds, and here the resin will not be as well photo-cured as in the centre. Light (b) has a lower, but more uniform, irradiance at about 1,200 mW/cm^2 that covers most of an 8-mm-diameter circle with over 24 J/cm^2 in 20 seconds. Clinically, if the beam profile consists of a small region of high irradiance compared with a more even 8–10-mm diameter of uniform irradiance, this means that the light tip must be very accurately positioned over the target, and the resin at the edges may receive an insufficient amount of light[54].

Light-curing unit ergonomics

In most laboratory experiments, direct access to the material to be cured is rarely a factor[1], and the light

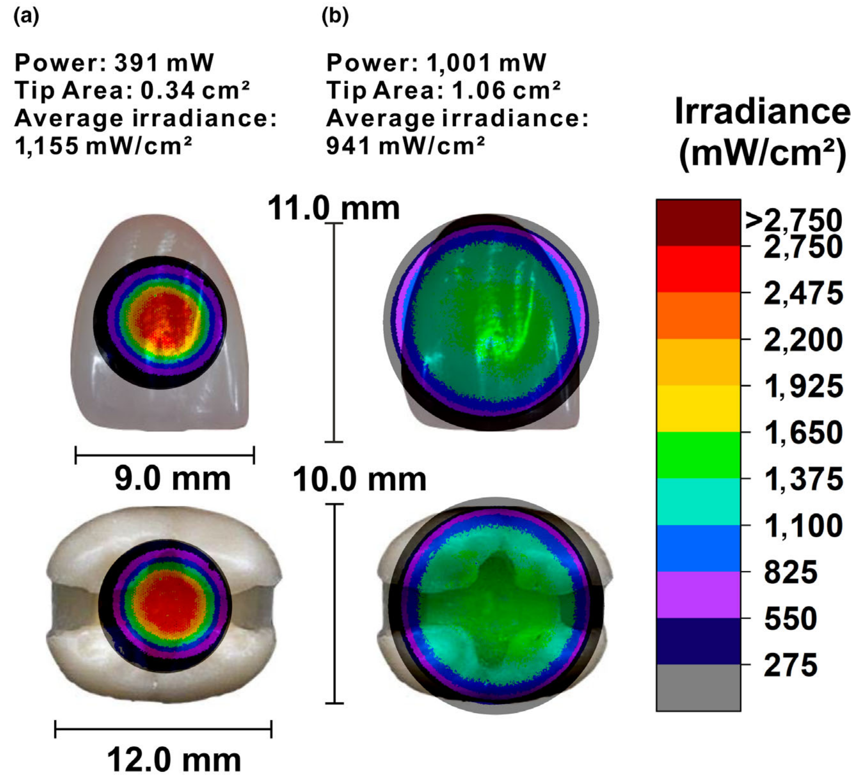

Figure 5. Two-dimensional irradiance beam profile of the tip of (a) and (b) curing lights scaled to 2,750 mW/cm^2 and superimposed over a maxillary central incisor or a mandibular first molar. Both lights deliver a similar average irradiance (1,155 mW/cm^2 and 941 mW/cm^2), but very different radiant power outputs and tip diameters. Light (a) has a small tip size and an undesirable irradiance hot spot of 2,750 mW/cm^2 at the centre, whereas (b) has a lower, but more uniform, irradiance at about 1,200 mW/cm^2 that covers most of the occlusal surface of the molar or the maxillary central incisor tooth.

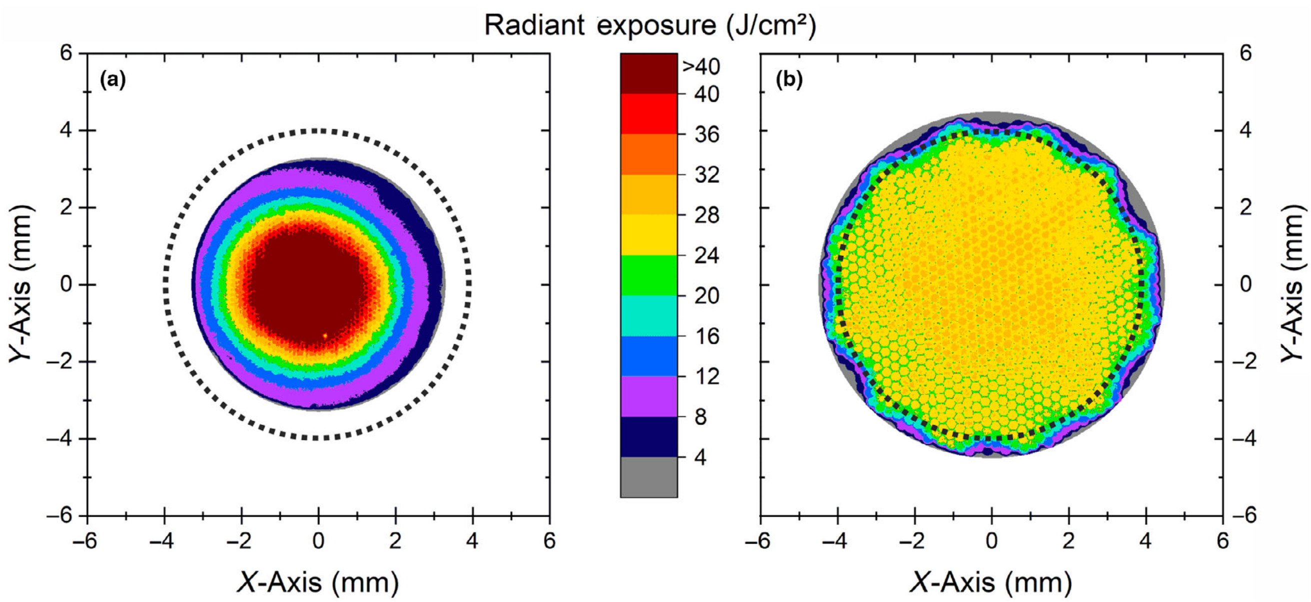

Figure 6. Radiant exposure (J/cm^2) delivered by two lights in 20 seconds. An 8-mm-diameter circle is drawn on both images. Note the smaller tip diameter and the uneven radiant exposure from light (a) compared with light (b) that emits more than 24 J/cm^2 uniformly across the 8-mm-diameter circle. Light (b), in comparison, has a 'hot spot' of high irradiance at the centre. This information would not be revealed in ISO 10650.

tip is precisely and rigidly positioned over the centre of the specimens. However, when used clinically, *Figure 7(a)* illustrates how the design of the LCU may prevent the light tip from achieving optimal access to all locations in the mouth[42,43]. This may cause the operator to increase the curing distance or

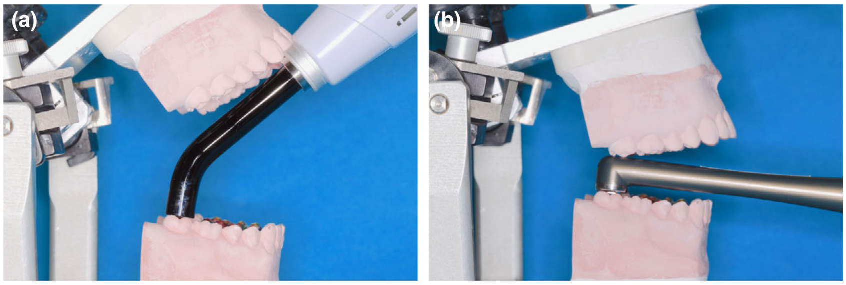

Figure 7. Although the light-curing unit (LCU) may work well on the laboratory bench, the design of the LCU will affect access to some teeth (a). A low-profile head (b) is preferred as it will allow better access to the posterior teeth.

angle the light tip. Doing so will reduce the amount of energy delivered and reduce the ultimate polymerisation of the RBC[3,59,60]. Consequently, a low-profile head (*Figure 7b*) that will allow better access to the posterior teeth is recommended[42,43,45]. The light tip should also be positioned both as close to the surface of the resin as is possible and perpendicular to the surface of the resin throughout the exposure cycle[19,61–65] (*Figure 7b*). Some manufacturers are now producing LCUs with sensing technologies that help the operator keep the LCU tip over the tooth[66,67]. If the light tip moves away from the tooth, the LCU first vibrates and then, if moved further away, the LCU turns off. This feature is similar to the 'lane assist' technology in cars, and should help the dentist keep the LCU tip on target and over the resin.

Blue light hazard

The dentist must protect the patient from harm, and employers should furnish a place of employment that is free from hazards that are causing or are likely to cause harm to their employees[25,68]. Most contemporary dental LED curing lights emit light between 430 and 480 nm, and the most damaging wavelengths of blue light to the retina are thought to be around 440 nm[69]. Exposure to blue light has also been reported to affect sleep patterns[25,70,71]. Although a 'blue light hazard' to the retina has not yet been shown to occur in humans, dental personnel may be both chronically and acutely exposed to much greater high levels of blue light than the general population. Because this potential 'blue light hazard' can be prevented by using the appropriate blue-light-blocking eye protection, it is recommended that appropriate eye protection in the form of orange 'blue-blocking' paddles, shields or eyewear should be used whenever the dental LCU is used[18,25,72–75]. Watching the position of the light tip while photo-curing will help ensure that the tip is kept over and close to the resin so that the bottom of the restoration will be adequately polymerised[19,54,61–65].

Infection control

It is important to recognise that the LCU can be a significant source of cross-contamination[76,77], and the manufacturer's instructions for disinfecting the LCU between each patient should be followed. Ideally, the LCU should have removable, autoclavable light guides and easily disinfected surfaces. However, an autoclavable light guide is impractical for many LCUs that do not use a light guide and instead have the LED emitter at the light tip (*Figure 1*). Of note, repeated autoclaving of fibre optic light guides can reduce the light output[78], and some surface disinfectants may both reduce the light transmission through the light guides and degrade the plastic LCU body[79,80]. In addition to wiping the LCU with the recommended surface disinfectants for the recommended time, plastic barriers or sleeves can be used to cover the LCU. However, the user must recognise that covering the light tip with an infection control barrier can reduce the irradiance delivered from the LCU by as much as 40%[81,82]. Thus, the output from the LCU should be regularly checked using a digital radiometer such as the Bluephase Meter II (Ivoclar Vivadent, Schaan, Liechtenstein) both without and with the same type of barrier that will be used on the LCU when treating patients. Then, depending on the percent decrease in the radiant exitance caused by the barrier, the clinician should increase the exposure times that they would use in the mouth[81–84]. The Bluephase Meter II has been shown to be an accurate (± 10%) dental radiometer that can measure the radiant power and, when the tip diameter is entered, this meter device can also report the radiant exitance[85,86]. As an added benefit, when the dentist measures the output from their LCU, they quickly realise the effects of battery discharge[38–41,43], the barrier they use[81–84], and both tip angulation and distance[23,44–46,60] have on the light received.

CONCLUSIONS

Globally there exists a large discrepancy between how long resin composite restorations are reported to last in well-controlled clinical trials[4,5], and how long they last when placed in most dental offices[6–9]. There may be many reasons for this discrepancy, but the general lack of understanding about the differences between LCUs, how to describe the output from the LCU, and how to use the LCU in everyday dentistry[10–19] may be contributing factors. The beam profile images (*Figures 3–6*) show that the single averaged 'irradiance' value used in the ISO 10650-standard[31] to describe the output from the LCU should be interpreted with caution. It is recommended that dental manufacturers and, where appropriate, the researcher should report the radiant power from the LCU, the spectral radiant power, information about the compatibility of the emission spectrum from the LCU with the photoinitiators used in dental resins, the active optical tip diameter from where the light is emitted, the radiant exitance at the light tip, the likely effect that distance from the tip will have on the irradiance received by a restoration, and the irradiance beam profile from the LCU. Clinicians should: (i) ensure that the LCU has been 'cleared'/'approved' for use in their country; (ii) regularly monitor the output from the LCU and take corrective action should the LCU output start to fall; (iii) follow the instructions for use; (iv) use an appropriate light tip diameter for the size of the restoration; (v) keep the light tip close and perpendicular to the resin; (vi) use appropriate eye protection; and (vii) use appropriate disinfection procedures.

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Conflict of interest

The authors state that they have no conflict of interest. Richard Price is the inventor of the MARC patient simulator that is marketed by BlueLight Analytics, Halifax, Canada, but he has not been associated with the company since 2012. Jack Ferracane is listed on an external advisory board for BlueLight Analytics. This appointment was made years ago, and he has not performed any duties for the company within approximately the past 5 years. Reinhard Hickel declares no conflict of interest.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1
Appendix S2

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