IN BRIEF

- Advances in the power output of light emitting diodes (LEDS) have allowed a LED light curing unit (LCU) with an 8 mm diameter light guide tip to achieve a similar depth of cure in a camphorquinone photoinitiated composite, as a halogen LCU.
- LEDs have long lifetimes and a more consistent output than halogen bulbs. The power density (irradiance) of an LED LCU does not have to be as high as a conventional halogen LCU to achieve the same depth of cure.
- Blue LEDs can be used as photodetectors and may be of future use in dental radiometers.
- When assessing the output from an LCU it is not only important to know the spectrum and irradiance, but also whether the emission is pulsed or continuous.

Optical power outputs, spectra and dental composite depths of cure, obtained with blue light emitting diode (LED) and halogen light curing units (LCUs)

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Objective To test the hypothesis that a prototype LED light curing unit, (LCU), a commercial LED LCU and a halogen LCU achieve similar cure depths, using two shades of a camphorquinone photoinitiated dental composite. To measure the LCUs' outputs and the frequency of the LED LCU's pulsed light, using a blue LED array as a photodetector.
Design Cure depth and light output characterisation to compare the LCUs.
Setting An *in vitro* laboratory study conducted in the UK.
Materials and Methods The LCUs cured A2 and A4 composite shades. A penetrometer measured the depth of cure. Analysis was by one-way ANOVA, two-way univariate ANOVA and Fisher's LSD test with a 95% confidence interval. A power meter and spectrograph characterised the LCUs' emissions. A blue LED array measured the pulsed light frequency from an LED LCU.
Results Statistically significant different LCU irradiances (119 mW/cm^2 to 851 mW/cm^2) and cure depths (3.90 mm SD ± 0.08 to 6.68 mm SD ± 0.07) were achieved. Composite shade affected cure depth. A blue LED array detected pulsed light at 12 Hz from the commercial LED LCU.
Conclusions The prototype LED LCU achieved a greater or equal depth of cure when compared with the commercial LCUs. LEDs may have a potential in dentistry for light detection as well as emission.

Curing of dental composites with blue light was introduced in the 1970s.[1] A typical dental light curing unit (LCU) normally combines a tungsten filament halogen bulb, a reflector and a filter, so that blue light in the 410 nm–500 nm region of the visible spectrum is produced. This is effectively absorbed by the camphorquinone (CQ) photoinitiator[2-4] present in many light cured composites. This light causes CQ excitation, which in combination with an amine, produces free radicals to polymerise the resin monomers.[5] Halogen LCU recommended curing times generally vary between 20 s and 60 s for a 2 mm increment of composite.

Halogen lamps found in most LCUs have an effective lifetime of approximately 50 hours.[6] The degradation of light output over time results in a reduction of the LCU's composite curing effectiveness.[7] Several studies[8-10] have shown that many halogen LCUs in clinical use do not produce their optimum output due to a lack of maintenance. Monitoring and maintenance of LCUs is thus extremely important. The lower effective limit of irradiance for halogen LCUs used in dental practice has been suggested to be 300 mW/cm^2.[11,12]

Other curing methods such as laser[13] and xenon arc[14] sources have been used to polymerise dental composites with the claimed advantage of reduced curing times. These devices are complex and costly compared with halogen LCUs, and lasers require elaborate precautions.

Blue electroluminescence from a LED formed by a silicon carbide crystal was discovered by H. J. Round in 1907.[15] The invention of a synthetic red LED in 1962[16] provided a new type of light source that was robust, efficient and suitable for portable battery applications. It was almost 30 years later that a bright blue LED was realised,[17] and in 1995, blue LEDs producing 4.8 mW were reported.[18] More recently ultra violet LEDs with a power output of 38 mW have been produced.[19] LEDs require no filters because of their relatively narrow emission spectra and can achieve lifetimes of over 100,000 hours with relatively little degradation.[20] These advantages of LEDs showed promise and blue LEDs were proposed for curing dental composites.[21,22]

Several studies using LEDs for curing have been reported.[23-32] When LED and halogen light sources of the same irradiance are used, the LEDs can achieve a greater cure depth when assessed by Knoop hardness and Fourier transform infra red (FTIR) spectroscopy degree of conversion analysis.[24] LED sources with a lower irradiance than the halogen source have also achieved a greater depth of cure[27] and can achieve a similar compressive strength.[28] Stahl *et al.*[29] demonstrated that the ISO4049[33] stan-

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dard for flexural strength properties for many composites was achievable with an LED LCU having a lower irradiance than a commercial halogen LCU.

Light guides with a tip of 8 mm in diameter are often used clinically, although 6 mm diameter tips were used in some earlier work.[25,27-29] To maintain the same irradiance in an 8 mm as a 6 mm diameter light guide requires 40% more optical power. We aimed to construct a more powerful LED LCU so that all LCUs tested had similar 8 mm diameter light guide tips commonly used clinically. Another objective was to include in the study the first commercially available LED LCU that we could acquire in the UK.

MATERIALS AND METHODS

The halogen LCU used was a Coltolux 4 model (Coltene/Whaledent Inc., Mahwah, New Jersey, USA) with a curved, parallel, fused glass fibre light guide. The commercial LED LCU was a LuxOMax (Akeda Dental, Lystrup, Denmark) with a curved, tapered, fused glass fibre light guide. The prototype LED LCU (LED63) was built by the first author and had a straight, tapered acrylic light guide. The LCU specifications are shown in Table 1.

The different layouts of the LED arrays of the LuxOMax and prototype LED LCUs are shown in Figure 1. The LuxOMax array contained seven unmodified 5 mm diameter blue LEDs of

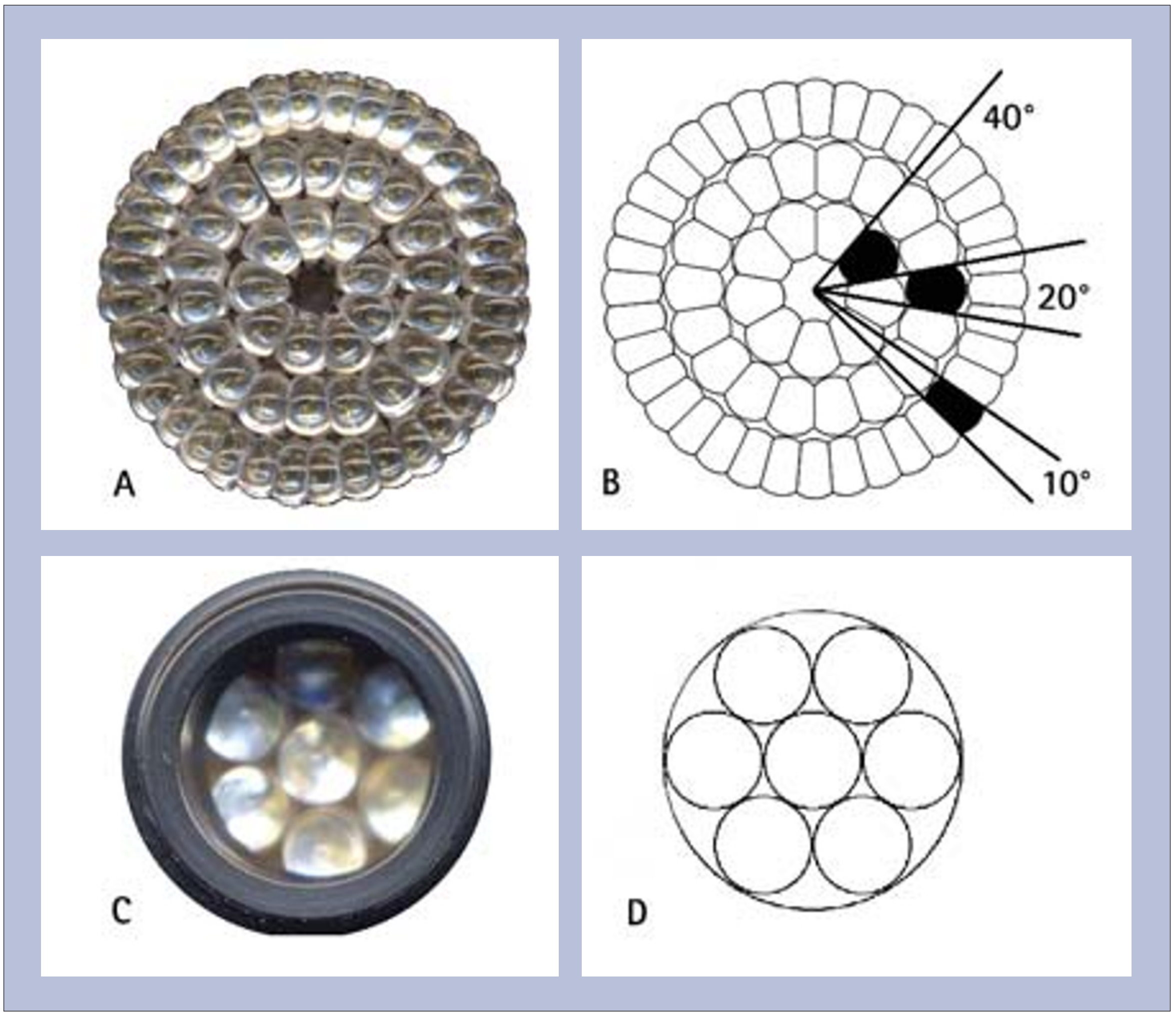

Figure 1 The arrays of both LED LCUs. A. Photograph of the LED63 showing layout of modified 3 mm LEDs. B. Schematic of the LED63 array with the LED modification angles for each ring. C. Photograph of the LuxoMax array of unmodified 5 mm LEDs. D. Schematic of the LuxoMax LED array.

Table 1 Technical data for the LCUs. An increase of over 300 mA through LED63 to give an average current of 45mA per LED only results in a 25 mW increase of optical power.

	LED63LCU driven at 40 mA per diode	LED63LCU driven at 45 mA per diode	LuxOMax LED LCU	Coltolux 4 halogen LCU
Light source	63 LEDs	63 LEDs	7 LEDs	75 Watt halogen bulb
Total driving current [mA]	2520	2835	600*	4241***
Mean current per LED [mA]	40	45	83*	N/A
Light guide tip ∅ [mm]	8	8	8	8
Optical power [mW]	310	335	60 (24)**	428
Irradiance [mW/cm^2]	616	666	119 (48)**	851
Spectral emission peak [nm]	457	457	466	485

* The input power is given in the instrument's manual as 3.6 watts and 6 volts, with a 0.1.W standby power. This LCU therefore consumes 600 mA and, assuming that the standby power is constant at 0.1 W, this gives about 580 mA through the LED array or 82.9 mA per LED.

** The value in brackets was the pulsed average soft-start power meter measurement for 1 s of the total 40 s exposure.

*** This value is for the bulb only, not the transformer unit and fan.

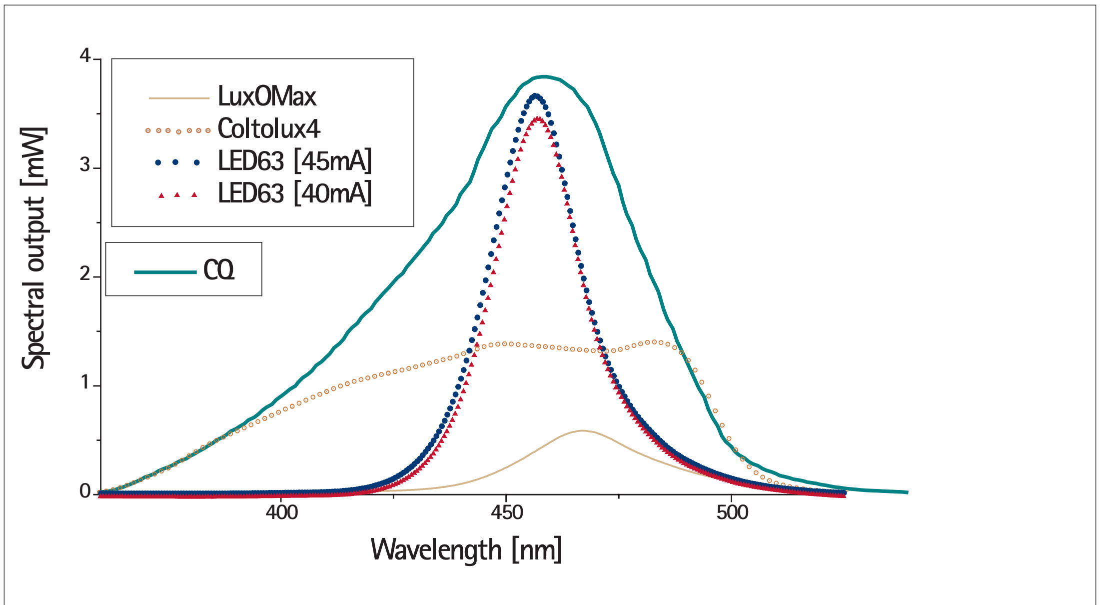

Figure 2 Graph to show the spectral power of the four LCUs used. Note the spectral power of the LED LCUs is concentrated over a relatively narrow bandwith compared with the halogen LCU. The camphorquinone (CQ) absorption curve is shown and scaled in arbitrary units on the y-axis to envelope the emission curves.

unknown origin, while the LED63 was constructed from 63 custom shaped 3 mm diameter blue LEDs (Nichia Chemical Industries Ltd., Anan, Japan). The light from the LED63 LCU was used in continuous wave mode and concentrated using a polymer optical taper. The amount of light transmitted depends on many factors, including the ratio of the areas of the taper's ends and its length.[34] No fan cooling was necessary for the LED LCU owing to efficient heat dissipation from the LEDs by copper heat sinks. The LuxOMax LED LCU was used in its highest energy mode. This allowed 39 s of full power and 1 s of reduced softstart power.

The power output for all LCUs was measured on a Molectron PM3 thermopile sensor connected to a Molectron 500D power meter (Molectron Detector Inc., Portland, Oregon, USA). The light guides were brought in perpendicular contact with the detector when recording the measurements. The spectra of the LCUs were measured using a MS127i imaging spectrograph with an Instaspec IV CCD array detector (LOT Oriel, Leatherhead, UK).

During the LuxOMax testing it was noticed that the softstart mode light appeared to flicker, indicating it may be pulsed. To investigate this observation, a detector was constructed with 27 custom shaped 3 mm diameter blue LEDs connected in parallel. The detector array was a similar design to the inner two rings of the LED63 (Figure 1). This array was directly connected to a Tektronix Model 465 100 MHz oscilloscope (Tektronix Inc., Beaverton, Oregon, USA). It has been suggested previously to use LEDs as wavelength sensitive detectors.[35] The peak wavelength of an LED used as a detector is shorter than the peak emission, and this can be between 20 nm and 60 nm.[35,36]

Two shades of a typical CQ photoinitiated hybrid composite were used, Spectrum TPH A2 and A4, (Dentsply DeTrey, Konstanz, Germany). Ten samples for each composite shade and LCU combination were cured for 40 s in a stainless steel mould with a diameter of 4 mm and depth of 8 mm. The LED63 was used in two different modes, one using an average driving current of 40 mA per LED, and the other 45 mA per LED respectively. Thus depth of cure was measured for a total of 80 specimens using a penetrometer as described elsewhere.[25,37]

A two-way univariate ANOVA was performed with the factors LCU and shade to determine the influence of the different factors on the depth of cure. In addition, a one-way ANOVA was applied on the depth of cure data for the shades A2 and A4 to determine the effect of the different LCUs on the depth of cure.

A Fisher's LSD test was used to discriminate between the means and to determine homogenous groups of the depth of cure. All statistical analyses were performed with the software Statgraphics Plus (Version 5.0) using a confidence interval of 95%.

RESULTS AND STATISTICAL ANALYSIS

The spectra for both the halogen and LED LCUs are displayed in Figure 2. The area under each plot represents the optical power of the LCUs. The power from the LED63 peaks at 457 nm and the LuxOMax LCU at 466 nm and is concentrated over a much narrower wavelength band than the halogen LCU.

Details of the cure depths and LCU outputs are shown in Table 2. The optical power outputs ranged between 428 mW for the halogen LCU and 60 mW for the LuxOMax. The optical power output of the LED63 LCU was 310 mW at 40 mA per LED and increased to 335 mW at 45 mA per LED. This represented an 8% rise for optical power (25 mW) and irradiance (50 mW/cm^2). The corresponding electrical power consumption increase was from 10.6 W to 12.0 W representing an increase of 12% (1.4 W).

Table 2 Penetrometer depth of cure values for each LCU shown as mean values for 10 test specimens with standard deviations. One-way ANOVA for the shades A2 and A4 and a Fisher's LSD test placed the depth of cure results in the homogeneous groups shown. Xs appearing in different columns are statistically significantly different at the 95% level, while those in the same column are not statistically significantly different.

LCU	Depth of Cure [mm] Shade A2	Depth of Cure [mm] Shade A4	Homogeneous Groups for Shade A2			Homogeneous Groups for Shade A4		
LED63 [45mA]	6.68 ± 0.07	5.49 ± 0.04			X			X
LED63 [40mA]	6.58 ± 0.05	5.44 ± 0.07		X				X
Halogen	6.61 ± 0.07	5.35 ± 0.07		X	X		X	
LuxOMax	4.69 ± 0.17	3.90 ± 0.08	X			X		

A two-way ANOVA showed that both LCU (p<0.001) and shade (p<0.001) had a statistically significant effect on the depth of cure. A Fisher's LSD test was used to identify statistically homogeneous groups within the LCUs. For both shades the LuxOMax achieved the statistically significant lowest depth of cure. The Coltolux 4 and LED63 produced statistically significantly different depths of cure for the shade A4. There was, however, no statistically significant difference between the Coltolux 4 and LED63 for the shade A2.

The mean increase in depth of cure with LED63 driven at 45 mA per LED compared with 40 mA per LED was only 1.5% (0.1 mm) for the light A2 shade and 1% (0.05 mm) for the darker A4 shade composite.

Measurement of the softstart phase of the LuxOMax LED LCU by the blue LED array connected directly to an oscilloscope resulted in a pulsed waveform being detected. The overall pulse cycle was 82 ms with a pulse width of 30 ms and an off-time of 52 ms. This gives a mark:space ratio of approximately 1:1.7 and a frequency of 12 Hz. Measurement of the LuxOMax unit at full power showed this to be a continuous wave output.

DISCUSSION

The light output from all LCUs differs in several respects. Previous work has shown that an LED LCU with a lower irradiance than a halogen LCU can achieve a greater depth of cure.[27] This is again confirmed here: LED63 had only 78% of the irradiance of the halogen LCU, yet exceeded the depth of cure. This has been explained previously by the effectiveness of different spectral outputs.[2-4,29] This lower output is also advantageous clinically, as less heat is being transmitted to the tooth and adjacent tissues. The human eye can only detect individual light pulses spaced at a minimum of 20 ms[38] and this equates to a maximum of almost 50 Hz with brief pulses. The results from the blue LED array and oscilloscope would appear to explain why the softstart mode of the LuxOMax appeared to flicker. Pulsing of a light curing source has been shown to have a different effect on curing,[39] so it is important to state whether the source is continuous wave or pulsed. This also confirmed that LEDs can act as detectors. It is possible that they may form the basis of a new type of dental radiometer in the future.

The composites used in this study were of differing shades but similar chemistry. The LED LCUs' emission spectra were well matched to the absorption spectrum of the CQ photoinitiator present in the composite. In composites where initiators are present that absorb outside the relatively narrow emission of the LED LCUs an LED curing may be less effective. In a previous study,[29] this was one explanation why the composite Solitaire™ (Heraeus Kulzer, Wehrheim, Germany) which contains photoinitiators outside the LED emission spectrum,[14] achieved relatively low flexural strengths compared with other materials tested. Xenon arc sources also have a narrow bandwidth and the suitability of xenon arc curing has been found to depend on the photoinitiators used in the composite.[14]

The results showed that an LED LCU with an 8 mm diameter light guide tip is capable of a statistically significantly greater depth of cure for a CQ initiated composite than a halogen LCU with a similar light guide tip diameter. This is an improvement on some previous work,[27,28] as a comparable depth of cure has been achieved between an LED LCU with a light guide tip with a 40% greater area. Different interchangeable LED arrays may become available to match different composites' photoinitiators, in the same way as different bandwidth filters are supplied with some xenon arc LCUs. Mixing LEDs of different wavelengths within the same array is another possible method of covering more than one photoinitiator. Another possibility is that composite manufacturers standardise, using just one photoinitiator. Future research will also aim towards comparisons of LED LCUs that have a 60° bend in the light guide so that access to all areas of the oral cavity is possible. Significant losses of transmission occur when large diameter light guides are bent. This means even more power from an LED array will be required, unless the LEDs are placed at the end of the light guide.

Although LED LCUs are capable of curing a similar depth of composite as a commercial halogen LCU, not all LED LCUs have the same performance, as shown in the current study. DeWald and Ferracane[40] showed that an adequate degree of polymerisation approximates to 50% of the depth of cure assessed by mechanical scraping to locate the interface between the 'soft and hard' parts of the specimen. A penetrometer attempts to record this position more objectively by exerting a reproducible consistent force. Using these criteria, it can be estimated that the commercial LED LCU reaches just above an adequate degree of polymerisation for a 2 mm increment of the lighter A2 shade composite. With the darker A4 shade, this 2 mm level is not reached. These results were for a composite that does not contain photoinitiators that absorb outside the emission spectra of the LEDs. Even lower levels of polymerisation may be expected if this were the case.[14] Clinically, it is preferable to have a greater safety margin to ensure adequate polymerisation, and LCUs should have possibly twice the minimum irradiance found to be required in the laboratory. Dentists should remember the guideline that doubling the irradiance of an LCU only approximates to a 20% increase in the depth of adequate polymerisation.[41] The results here should help dentists to weigh the different factors when choosing the most appropriate LCU for their application. Blue LED technology continues to improve and appears to have a useful future role in dentistry.

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