

Qualitative Beam Profiling of Light Curing Units for Resin Based Composites

Keywords

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ABSTRACT

This study investigates two technically simple methods to determine the irradiance distribution of light curing units that governs the performance of a visible-light curing resin-based composites. Insufficient light irradiation leads to under-cured composites with poor mechanical properties and elution of residual monomers. The unknown irradiance distribution and its effect on the final restoration are the main critical issues requiring highly sophisticated experimental equipment. The study shows that irradiance distributions of LCUs can easily be determined qualitatively with generally available equipment. This significantly helps dentists in practices to be informed about the homogeneity of the curing lights.

INTRODUCTION

UV or visible-light cured (VLC) resin-based composites (RBC) were established in dentistry in the late 1970s.^{1,2} During the last 40 years, the light curing unit (LCU) has changed from quartz-tungsten halogen (QTH) to plasma arc lamps (PAC) and argon ion laser and further to light emitting diodes (LED).³ The current states of art of LCUs are polywave LED LCUs, known as third generation LCUs. These emit in several wavelength ranges to activate different types of photoinitiators.⁴ Nevertheless, the older techniques such as QTH or PAC are still in use.³

Typically, two kinds of basic LCUs are used. The first type has a light guide tip which directs the light from the light source to the restoration. These light guide tips are fiber optics of high optical quality. Therefore, the shape of the light source or parts of the internal design is often recognizable on the light guide tip exit (hereinafter called the tip exit). The second type is exclusive to LED LCUs which have LEDs on a rod end with a lens or a window in front of them.

Moseley *et al.*⁵ showed in the 1980s that LCUs exhibit an inhomogeneous irradiance distribution across the tip exits. The first studies were performed with photocells or optical fibers connected with a UV-Vis spectrometer which were positioned in front of the tip exits to scan the irradiance distribution.^{5,6} Vandewalle *et al.*⁷ used a digital camera known as "laser-beam profiler" to take images indirectly onto a target screen of an entire tip exit in one shot to determine the irradiance distribution.

Several studies showed that the irradiance distribution affects the mechanical properties of RBCs.⁶⁻¹⁰ The degree of conversion and the resulting mechanical properties depend on the irradiance delivered to the RBC.¹¹⁻¹⁵ Areas of VLC RBCs exposed to a high irradiance show higher hardness values than those exposed to lower irradiance.^{6,9} Low irradiance leads not only to a lower surface hardness but also to lower depth of cure causing under-cured or uncured layers at the bottom of the restoration.

An issue for dentists is that they do not know to what extent the irradiance output of their LCU is inhomogeneous. In the case of pronounced irradiance inhomogeneity, the curing process depends strongly on the position of the tip exit above the restoration yielding possibly insufficient final material properties.

In the present study two different methods are investigated to qualitatively determine the irradiance distribution from LCUs. The first method was to take images of the irradiance distribution of activated LCUs with a single lens reflex camera (SLR) in "true color". The second method was to image the irradiance distribution with the iPad using the "thermal camera" program in pseudo color. The results were compared to images performed with a laser-beam profiler as the reference method.

MATERIALS AND METHODS

Six different LCUs were tested in this study, Table 1. Five LCUs were equipped with fiber optic light guide tips and one with a window in front of the LED. A laser-beam profiler, a SLR and an iPad were used to determine the irradiance or irradiance distribution of these LCUs. The quantitative light measurement values with integrated sphere and laser-beam profiler are denoted as irradiance while the qualitative light measurements with the SLR and the iPad are denoted as intensity. The experimental equipment is listed in Table 2.

POWER OUTPUT MEASUREMENT AND BEAM PROFILING

The power output of the LCUs was measured to ensure the correct functioning of the LCUs in respect to the manufacturer specifications. The power output of a Celalux 1, Celalux 2 and Bluephase 20i was firstly measured with an integrated sphere (Labs sphere) connected to a UV-Vis spectrometer by integrating the spectra between the wavelengths $I_{min}=350nm$ and $I_{max}=550nm$. Secondly, these three LCUs were measured

with a laser power meter (Thorlabs PM100D) to compare both methods and to ensure that the laser power meter delivers comparable results to the integrated sphere.

The power output of a Polofil Lux, Elipar S10, and Smart-Lite PS were measured only with the laser-power meter after the results of the integrating sphere and laser power meter corresponding was checked. The irradiances were calculated by dividing power output through the effective tip exit area determines by measuring the diameter by a caliper.

The irradiance distributions of Celalux 1, Celalux 2 and Bluephase 20i were determined using the laser-beam profiler as the reference method. The LCUs were placed in contact to a frosted glass shield (DG2X2-1500, Thor Laboratories, Newton, NJ, USA) in front of the laser-beam profiler, Figure 1. A neutral density filter set (ND1/ND2, Ophir optics) was placed between the laser-beam profiler and the optic to prevent overexposure of the laser-beam profiler. The intensity images were represented in arbitrary units and had to be transferred to irradiance in mW/cm^2 with the calibration factor f_{cal}

$$f_{cal} = \frac{P_{out}}{I_{total} \cdot A_{pixel}} \tag{1}$$

whereby P_{out} is the total power output in mW of a LCU, I_{total} is the total amount of all arbitrary units of the image, and A_{pixel} is the area of one pixel of the laser-beam profiler.

Then the irradiance per pixel $I_{r_{pixel}}$ is given by:

$$I_{r_{pixel}} = f_{cal} \cdot I_{pixel} \tag{2}$$

with the intensity of one pixel I_{pixel} in arbitrary units.

IMAGING OF THE LCUS WITH SLR AND IPAD

As SLR camera was used a Canon EOS 60D with a 18-200mm lens. The SLR images were shot with inactivated and activated LCUs. The LCUs were mounted on a stand with a distance of 80 cm to the SLR and the focal length was 200mm. The aperture of the camera lens was between 13 and 20 and the length of exposure was chosen to prevent overexposure between 1/5000 s and 1/8000 s.

Table 1. Light curing units

Unit	Manufacturer	Type	Irradiance [mW/cm^2]	
			Integrated Sphere	Laser Power Meter
Celalux 1	Voco GmbH, Cuxhaven, Germany	Monowave LED LCU	1172 (6.2)	1107 (30.2)
Celalux 2			1264 (9.5)	1255 (33.7)
Polofil Lux			n/a	1156 (2.2)
Bluephase 20i	Ivoclar Vivadent, Schaan, Lichtenstein	Polywave LED LCU	2222 (24.2)	2211 (15.1)
Elipar S10	3M ESPE AG, Seefeld, Germany	Monowave LED LCU	n/a	1117 (2.1)
SmartLite PS	Dentsply DeTrex GmbH, Konstanz, Germany	Monowave LED LCU	n/a	1246 (34.9)

Table 2. Experimental equipment

Canon 60d		SLR Camera (Resolution: 18 Megapixel)
Canon EF 18-200 mm	Canon, Ota, Tokyo, Japan	Zoom lenses, Model EF-S 18-200/1:3,5-5,6 IS
iPad 2	Apple Inc., Cupertino CA, USA	Tablet PC, Model A1396 (GSM) (Resolution front camera: 0.3 Megapixel)
DHG Light Control Filter ND 8	Dörr, Neu-Ulm, Germany	Neutral density filter, Optical Density: 0.9
LabSphere 6"	LabSphere, North Sutton, NH, USA	Integrated Sphere
Ocean Optics USB4000	Ocean Optics, Dunedin, FL, USA	UV-Vis Spectrometer
LBA USB-L070 Beam Profiler	Ophir-Spiricon, Logan, UT, USA	Laser Beam Profiler (Resolution 0.3 Megapixel)
Stackable Filter ND1/ ND2		Neutral Density Filter, Light transmission ND1 ~ 10%, ND2 ~ 1%
Thorlabs PM100D		Power Meter
Thorlabs S310C	Thorlabs GmbH, Dachau, Germany	Thermal Sensor

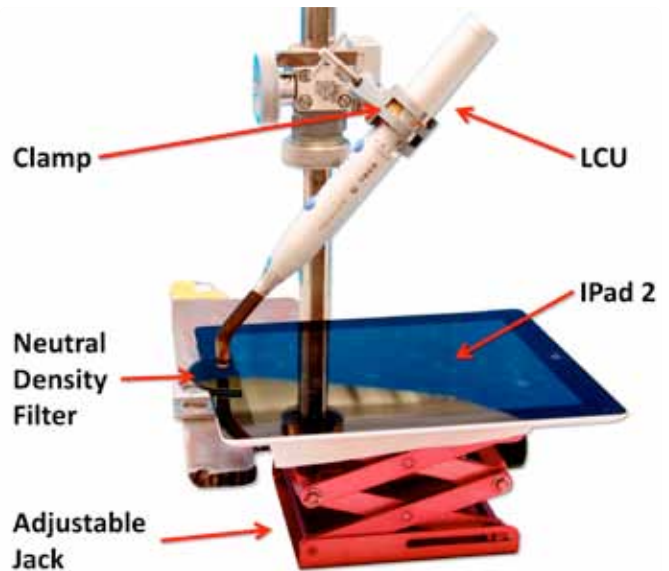


Figure 2: Experimental Setup with an iPad as detector

The iPad images were collected with the “thermal camera” function of the standard installed camera program “photo booth”. The iPad was placed on an adjustable jack, Figure 2. Due to the high radiant power from the sources, two neutral density filters (ND 8, Dörr, Neu-Ulm, Germany) were used to prevent overexposure. These filters were placed in front of the camera on an iPad (Apple Inc. Cupertino, CA) to avoid overexposure.

The light guide tip exits were fixed parallel to the iPad surface over the front camera. The LCUs were moved up and down until focused images were shown on the screen. Depending on the LCU the distances between the tip exits and the camera were in a range of 5 to 15cm. The different distances are necessary because of the different focus of the light beam from the LCUs and the autofocus operation of the iPad. The settings of length of exposure and aperture were automatically chosen by the program and are not under the control of the user.

RESULTS

The power outputs and the calculated irradiances of the six tested LCUs correspond to the manufacturer’s data, Table 1. ¹⁶⁻²⁰ Both methods, the integrated sphere and the laser power meter delivered similar results, Table 1. The images of the laser-beam profiler, Figure 3, look very similar to the activated tip exit SLR and iPad images for Celalux 1, Celalux 2, and Bluephase 20i, Figure 4 A, B and D which were tested with all three methods. The center spot areas for Celalux 1 and Celalux 2 are clearly seen in each image. Additionally, the laser-beam profiler and iPad images show the higher irradiance area at the 5 o’clock position. The lack of irradiance at the 3 o’clock position and the c-shaped high irradiance area around the center spot of the Bluephase 20i is also shown in each activated image. Furthermore, the SLR image shows a purple spot at the 3 o’clock position, Figure 4 D2. This spot is caused by the 410nm area of the polywave LED chip of the Bluephase 20i.

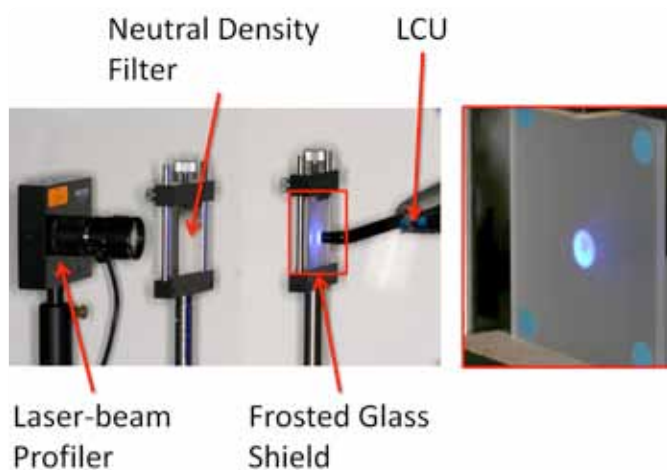


Figure 1: right, experimental setup of the laser-beam profiler with a Bluephase 20i in front of the frosted glass shield; left, shining Bluephase 20i through the frosted glass shield

The images of the inactivated tip exits of Celalux 1, Celalux 2, and Bluephase 20i do not correspond with the other methods, Figure 4 A1, B1, and D1. However, the Polofil Lux, Elipar S10 and SmartLite PS disabled SLR images correspond with the activated SLR and iPad images.

Imaging of very homogeneous LCUs such as Polofil Lux, Figure 4 C3, is difficult with the iPad as the difference in irradiance between the highest and lowest levels of output is used to create the pseudo color image. On very homogeneous LCUs a small deviations of parallelism between tip exit and camera may pretend an inhomogeneous irradiance distribution. In this case the position of the irradiance distribution is not fixed and is moving with a change of the angle. Additionally, the automatic adjustment generates the same pseudo color image of the intensity distribution which is qualitatively identical, but different with respect to the irradiance level, Figure 5.

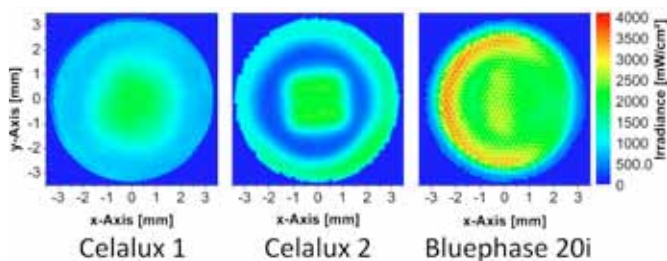


Figure 3: Laser-beam profiler images of Celalux 1, Celalux 2 and Bluephase 20i in Turbo Mode

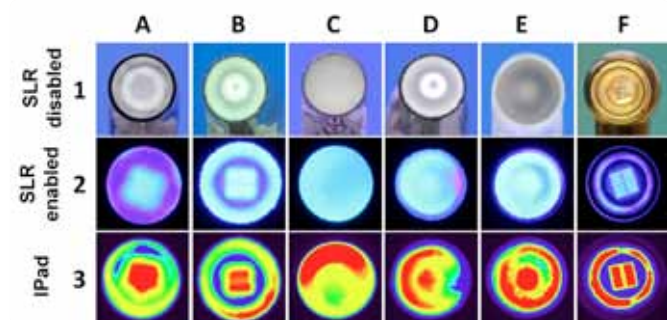


Figure 4: Images of light guide tip exits inactivated and activated with SLR and iPad: A Celalux 1, B Celalux 2, C Polofil Lux, D Bluephase 20i, E Elipar S10, and F Dentsply SmartLite PS

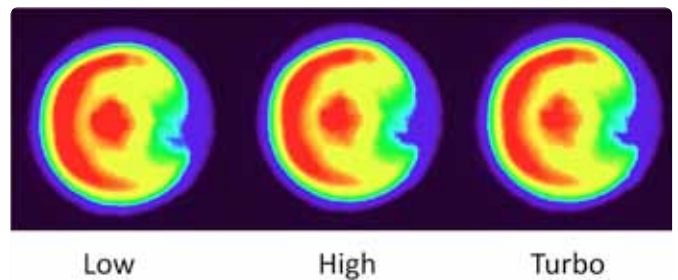


Figure 5: Pseudo color images of Bluephase 20i in Low, High, and Turbo mode made with iPad

DISCUSSION

Each LCU has a characteristic distribution of irradiance which may affect the quality of a restoration.^{5-9,21} The clinician should endeavor to understand the distribution of the irradiance from a LCU. The three different methods laser-beam profiler, SLR and iPad give the user the ability to determine the irradiance and intensity distributions of LCUs.

The laser-beam profiler as the reference method has the highest experimental effort of all methods and is not practicable for a normal clinical practice. Additionally, the laser-beam profiler setup is slightly different from the SLR and iPad setup with the frosted glass shield as target for the LCU light beam. The frosted glass shield is the projection screen and it is necessary to determine the irradiance distribution with increasing distance from the LCU to a surface. A resulting irradiance distribution depending on the distance cannot be displayed without a target. Price *et al* show the influence on the irradiance distribution and output, which show that the top hat factor as measure for the inhomogeneity is not change with increasing distance.²² However, the output is change and this may cause of insufficient curing intensified by lack of irradiance cause of inhomogeneous irradiance distribution. Damages of the frosted glass shield or incorrect alignment of the LCUs can cause in reflections and incorrect presentation of the irradiance distribution. Nevertheless, for the determination of an irradiance distribution at 0mm, a frosted shield is not necessary because of the exit window of the light guide tip which is the target in the SLR and iPad setup.

The results show that each LCU has a characteristic irradiance distribution which differs from each other. The SLR has the highest resolution of the three methods and provides the best image quality, Table 1. However, the SLR images of the inactive light guide tips do not coincide with the real intensity distribution in all cases, Figure 4. Therefore, this method is inappropriate to determine the intensity distribution. Additionally, the visual examination of an active light guide tip by eye sight is extremely hazardous and totally contraindicated.

The comparison between the images of activated LCUs with the laser-beam profiler, SLR and iPad imaging shows that all the above methods are suitable to determine the irradiance distribution.

The SLR imaging of the activated LCU in “true color” shows similar intensity distribution as the laser-beam profiler for the tested LCUs Celalux 1 and 2 and Bluephase 20i with both methods. SLR imaging is advantageous due to the lower experimental effort, e.g. an adjustable jack is not necessary. However, the SLR images provide a lower contrast than the laser-beam profiler and the iPad imaging, Figure 3 and 4. Nevertheless, the results show that SLR imaging is an appropriate method to qualitatively characterize the intensity distribution of activated LCUs.

The iPad imaging in pseudo color shows similar intensity distribution as the laser-beam profiler. The experimental effort is slightly higher than the SLR imaging considering the precise parallel adjustment of the tip exit above the iPad camera is required. Furthermore, focusing is easier with an SLR. Nevertheless, the iPad imaging gives a good qualitative overview of the intensity distribution to the clinician.

In contrast to the clinical situation, the used experimental setups in this study were fixed cameras in relation to the LCUs. The dentist cannot stabilize the LCU in relation to the restoration during the irradiation by hand. The movement of the light guide tip over the restoration may have a positive effect to diminish the intensity distribution effects of the LCU. However, some facts seem to be at odd to this assumption. The specific intensity distribution is normally unknown to the user and the movement of the LCU in relation to the restoration is arbitrary, which leads to a not reproducible curing. Additionally, the amount of energy to the restoration depends on the user and their level of instruction and training.²³ Instructed user delivered a higher amount of energy to the restoration as not trained user, which can lead to an insufficient curing of the restoration. Therefore, a user without the knowledge and awareness to the intensity distributions of LCU would likely not lead to a positive result. Furthermore, the fast curing processes of VLC-RBCs exceed the vitrification point in the first few second after the start of exposure.^{9,24} As a result, the pattern of the intensity distribution is shown in the formed polymer network of the restoration. This reduces the chance to diminish the impact of very inhomogeneous intensity distribution of LCUs by moving.

In summary, the SLR and iPad imaging are both adequate methods for a qualitative estimation of the intensity distribution on LCUs. Due to the pseudo color images, the iPad imaging is easier to interpret compared to the images from the SLR camera. Both methods allow the user to quickly and qualitatively determine the intensity distribution of any LCU and help guide choice of the best position above the restoration for exposure. In general, all SLRs should suitable to determine the intensity distribution of LCUs provided that the SLR is not overexposed.

CONCLUSION

The three methods of LCU imaging showed the same qualitative irradiance distribution for the tested LCUs. The laser-beam profiler images can be scaled to represent the irradiance values. The SLR images have a higher resolution than the laser-beam profiler, but the contrast is often too low. The iPad images have a lower resolution than SLR images but the option of pseudo colorization results in irradiance distribution is very similar to the laser-beam profiler. The pseudo color iPad imaging is a useful tool for the qualitative evaluation of irradiance distribution. Furthermore, the tip exit images of inactive LCUs give no reliable information about the intensity distribution.

Additionally, it is clear that the irradiance distribution is governed by the internal design but the user has to consider where the highest intensity area of a LCU is to ensure a proper curing for restorations.¹⁰

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