BEAM PROFILE CHARACTERIZATION OF A DENTAL LIGHT CURING UNIT USING A SPECTROMETER-BASED METHOD

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ABSTRACT

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Aim: The study aimed to characterize a broad spectrum light curing unit (LCU) by measuring the light beam profile output of the LCU using a spectrometer-based method and correlate it with a standard camera-based beam profile method.
Materials and Methods: A broad spectrum LED LCU (Ascent OL5, CAO Group) was mounted above a spectrometer (MARC® Resin Calibrator, BlueLight Analytics) at exposure distances of 1.0, 1.5 or 2.5 mm. The position of the center of the LCU was aligned with the spectrometer's cosine corrector sensor, and then moved in 1-mm increments in the x-y plane, while concomitantly recording the irradiance. The recorded irradiance was systematically organized and reported in function of the distance from the center of the LCU exiting window. Using a standard camera-based beam profiler, a beam profile of the LCU was obtained and the above approach was emulated to the beam profile. For both methods, the irradiance decreases related to the value measured at the center position was analyzed by calculating the slope, using a linear correlation.
Results: Both methods showed that moving away from the center showed decreased irradiation. The beam profile of the LCU is asymmetric. The inhomogeneity of the beam was slightly lower with farther distance from the LCU's light exciting window.
Conclusion: The spectrometer-based method was able to characterize the beam profile of the LCU and can be used in the evaluation of LCUs.

Keywords: light curing units, beam profile, spectrometric analysis.

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1. Introduction

Light curing has revolutionized the placing of composite restorations [1]. Furthermore, light curing is used for multiple other applications such as cementing dental fixed prostheses, including indirect restorations made from ceramics or composites, sealing fissures, and bonding orthodontic brackets. Nowadays, market available light curing units (LCUs) are very well build and really intuitive which make dentists assume that light curing is a simple procedure, however it is not. First, to be cured properly, a resin-based composite (RBC) must be exposed to a visible light energy at the proper wavelength range (blue or blue and violet) and a radiant exposure ranging from 8-16 J/cm^2 [2], which means that, depending on the irradiance the RBC is receiving, exposure times up to 60 s are required [3]. The key problem is that dentists believe that a single irradiance value of LCU reported and stated by the LCUs' manufacturer homogeneously reaches the entire RBC surface, which is not the case [4].

It starts with the correct positioning of the LCU on top of the RBC, controlled by the dentist only. Very large differences have been documented when comparing the light curing of untrained vs trained dentists [5]. Furthermore, the dentist should be aware that the irradiance of an LCU diminishes as the distance increases from the light output window [6] and, besides that, the cleanliness aspect of the LCU light tip is fundamental, because any residual RBC stuck onto the light exiting window may also reduce the light irradiance, which is a huge problem that affects the geometry of the light tip which may create shadows [7,8], and thus the depth of the cure may be reduced. Furthermore, depending on their composition (filler, resin mix, pigments and opacifiers), RBCs absorb more or less light [9], which reduces the depth of the cure as well. Based on this knowledge, recommendations for dentists about how to light cure were formulated by a group of researchers, industry representatives, editors and dentists [10-12]. This group is very active and has published recommendations in dental journals, newsletters and websites of associations worldwide.

Multiple studies have shown that the LCUs as used in practices do not yield the light intensity output stated by the manufacturers [13-16]. The outcome of light curing can be influenced as well by factors which are governed by the design of the LCU and of course by the RBCs themselves [9,17]. The characteristics of the LCUs have a strong influence on the incident irradiance received by a material due to a multitude of factors. This was observed for the first LCUs operating in the visible light range, based on Quartz-tungsten halogen bulbs which had been developed for other purposes than dentistry [18]. These light curing units had the advantage of a broad light spectrum [19]. However, since only the blue light was usable to cure RBCs, infrared-blocking blue bandpass filters (at 510 nm) were built in the LCUs. These filters would deteriorate over time, diminishing the light emission properties of the LCUs [20]. There were more characteristics that basically made them problematic [21], such as instability of the output, spectral distribution and unreliable timers. Some LCUs had a quite homogeneous beam profile, which means that the surface of the irradiated composite gets the same energy density on every area. This is possible because in a halogen light the hot wire creating the light is almost a point light source, which can be captured with a reflector and guided into a beam. However already in 1986 it was shown that some LCUs had an inhomogeneous light beam [21]. This was confirmed using an acrylic optical fiber with a 1 mm diameter moved at 1mm steps in x-y direction in front of the light emitting tip of the LCU. With this method the local light intensity of three QTH lights, a plasma arc light and a LED light was measured [22].

For many reasons LED LCUs were a big improvement. LEDs are not considered a point light source, since they have the shape of a flat surface emitting the light. Early LEDs had very little power (1.2 mW) and thus were not usable for light curing devices [20]. But, over the years they became much more powerful (e.g. 123 mW), thus multiple LEDs were used as a light source which made it difficult to bundle the emitting light [20]. Modern LED LCUs use 1-8 LEDs in an array which is flat [23], which makes bundling the light more difficult and may result in an inhomogeneous beam profile, despite being a mono-wavelength unit (peak at around 450-470 nm). Finally, the last step in development is the broad spectrum LED LCU, which uses different types of LEDs, emitting light with different wavelengths (violet light (380 – 420 nm) and blue light (420 – 495 nm) [8,20]. Therefore they are able to activate different types of photoinitiators [24]. However, these LED LCUs show more or less pronounced inhomogeneity of the beam profiles [25-28]. This means that not every point on an irradiated surface gets exposed to the same level of irradiation from the different wavelengths, especially in depth [29-31]. Thus, if the dentist aims for a short exposure time, some areas of the irradiated RBC may not obtain the minimally required light radiant exposure for optimal monomer conversion [24].

The power of the light source determines the energy it can emit; the design of the optical system to capture and bundle the light emitted from the light source determines the degree of spread of the light after it exits the light curing fiber bundle or lens. Turbo tips, which concentrate the light on a smaller surface to increase the irradiation usually have a larger spread than conventional tips [24]. Usually, the spread is considerable, yielding to less irradiation the farther away the target RBC is from the light exciting window [25,26].

A light beam profile is the 2D irradiance intensity plot for a camera-based beam profiling system, requires a thermopile (power meter), a spectrometer, a CCD or CMOS camera, a modern computer with a frame grabber card to digitize the signal, and software for controlling the frame grabber card, displaying beam profiles and making respective quantitative calculations. Also, an optomechanics apparatus, such as diffusive glasses and band pass filters, is almost always needed to attenuate and/or filter the light beam before going into the camera [27,28]. In general, it cannot be bought together, and requires knowledge to buy the complete and right equipment. Moreover, the operator needs to know how to use all these parts together.

Thus, the objective of the present study was to characterize a broad spectrum LED LCU with a known inhomogeneous beam profile using a spectrometer-based method and correlate it with a standard camera-based beam profile method. The following null hypotheses were tested: 1) The irradiation is at the same level all over the irradiated surface. 2) The irradiation as captured with the spectrometer-based method is similar to the irradiation shown by a standard camera-based beam profiler.

2. Materials and Methods

For this method-validation study a broad-spectrum LED LCU (Ascent OL5, CAO Group South Jordan, UT, USA) was used. Its design leads to the assumption that it will generate an inhomogeneous beam profile, since it has one LED emitting blue light mounted in the center and 4 small LEDs emitting violet light mounted at the periphery (Fig. 1). The LCU was attached to an x-y-z positioning device mounted on an optical bench in order to standardize the positioning of the light beam centered above the cosine corrector light signal collector of a spectrometer (MARC® Resin Calibrator, BlueLight Analytics, Halifax, Canada) with the handle towards the right side ("EAST", Fig. 2) at an exposure distance of 1.0, 1.5 or 2.5 mm. The diameter of the cosine corrector was 3.9 mm. Using the translation stage, the position of the geometrical center of the LCU was first aligned with that of the cosine corrector and then moved in 1-mm steps in the x-y plane ("EAST" – "WEST" and "NORTH" – "SOUTH") (Fig. 2).

The irradiance was assessed at each above described condition. The irradiance loss was visualized using bar graphs for the East-West (long axis of the LCU) and the North – South direction. The slopes of the irradiation decrease were calculated and compared.

To obtain standard camera-based beam profile images, the same LCU was attached to an x-y-z positioning device mounted on an optical bench in order to standardize the positioning of the light beam in contact with a diffusive surface of a frosted diffuser target (DG20-1500, Thorlabs, Inc., Newton, NJ, USA) while the resulting image was recorded using a camera (NEX-F3, Sony Corporation, Tokyo, Japan) with a 50 mm focal length lens. To assess the irradiance distribution of the different LED emission wavelengths from the broad spectrum LED, the beam profiler was used with the addition of bandpass filters (Thorlabs,

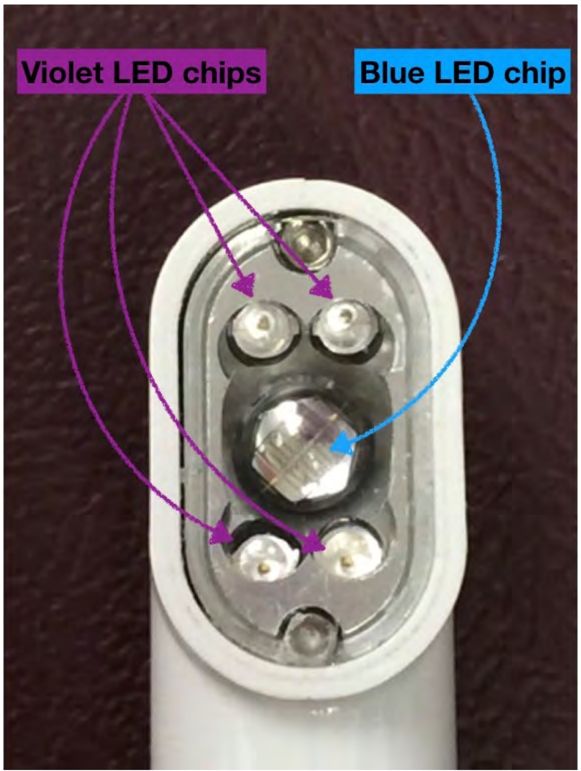

Figure 1. LED positions in the Ascent OL5 LCU.

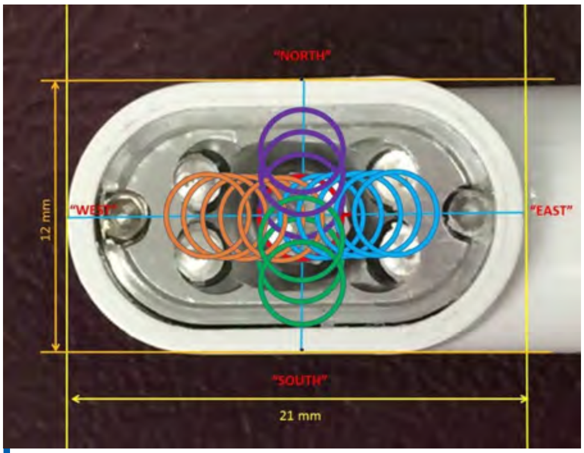

Figure 2. Measuring points as related to the position within the light exit window. Blue cross = geometrical center of the light exiting window. Orange circles = "WEST", Light blue circles = "EAST", Purple circles = "North" and green circles = "SOUTH".

Inc., Newton, NJ, USA) placed in front of the camera lens. A bandpass filter centered first at 400 nm with a 40 nm full width at half maximum (FB400-40) was used to identify the LED chips with spectrum emission peaks at 400 nm (violet light). A different bandpass filter, centered at 450 nm with a 40 nm full width at half maximum (FB450-40) was used to identify the LED chips generating emission peaks near 450 nm (blue light). To produce calibrated images and data showing the irradiance patterns across the surface of the broad spectrum LED, the mean power values, obtained using the MARC resin calibrator were entered into an open source optical analysis software (Fiji, ImageJ, National Institute of Health, Bethesda, MD, USA) [32] to process the camera-based method beam profile images. The total spectral power output was integrated with each bandpass filter spectral optical density to calibrate each image. The scaled numerical data associated with each image were exported into a computer graphic software (Origin Pro, OriginLab Co., Northampton, MA, USA).

The beam profiles were captured at 1, 1.5 and 2.5 mm from the light exciting window of the LCU and further analysis of the local intensities was performed the identical way as done with the MARC® resin calibrator. A virtual aperture of 3.9 mm was created using the computer graphic software and the average irradiation on this surface was measured by first placing this aperture in the geometrical center of the beam profile and then moving it into 1 mm steps in the "EAST – WEST" and "NORTH – SOUTH" direction. Bar graphs comparable to the ones created with the spectrometer-based method were generated. In a second step, to calculate the magnitude of the decrease in the light irradiance according to the distance from the center of the LCU, a linear correlation fit was made to compare the slopes produced by the spectrometer-based method with the slopes generated from the camera-based method.

3. Results

At 1 mm distance from the light exciting window, the broad-spectrum LED had a total irradiance of 1159 mW/cm^2, however, 1088 mW/cm^2 was within the blue wavelength range (420 - 495 nm) and only 71 mW/cm^2 was within the violet wavelength range (380 – 420 nm). As shown in Fig. 3, it is clear that the majority of the power emitted (mW) by the broad-spectrum was within the blue wavelength range and the violet emission from this LED is considered insignificant.

The results of the irradiance measurements at 1, 1.5 and 2.5 mm distance from the light exciting window are shown in Fig. 4. As expected, there is a decrease in irradiance the farther away the measuring area is from the center. To allow better direct comparisons, the slopes of these decreases were calculated as shown in Table 1. Higher absolute value means greater rate of reduction in irradiance with distance from the geometric center of the LCU. Note that the farther away the light source is from the sensor, the flatter the slope, which means that the inhomogeneity of the beam profile decreases.

Fig. 5 shows the beam profiles obtained at 1, 1.5 and 2.5 mm distance from the light exciting window of the LCU. Note the spread of the beam and the inhomogeneity of the irradiation. Fig. 4c, Fig. 4d and Table 1 show the data as extracted from the beam profiles. Note the similarity of the pattern.

4. Discussion

The LCU used in this study was selected because based on its design an inhomogeneous beam profile was to be expected. The objective of the study was to use a spectrometer-based method to detect inhomogeneity in the light beam profile output of a LCU. Therefore, it makes sense to use a LCU, where this characteristic is to be expected.

The Ascent OL5 broad spectrum LCU had a significant higher amount of blue light being emitted than violet

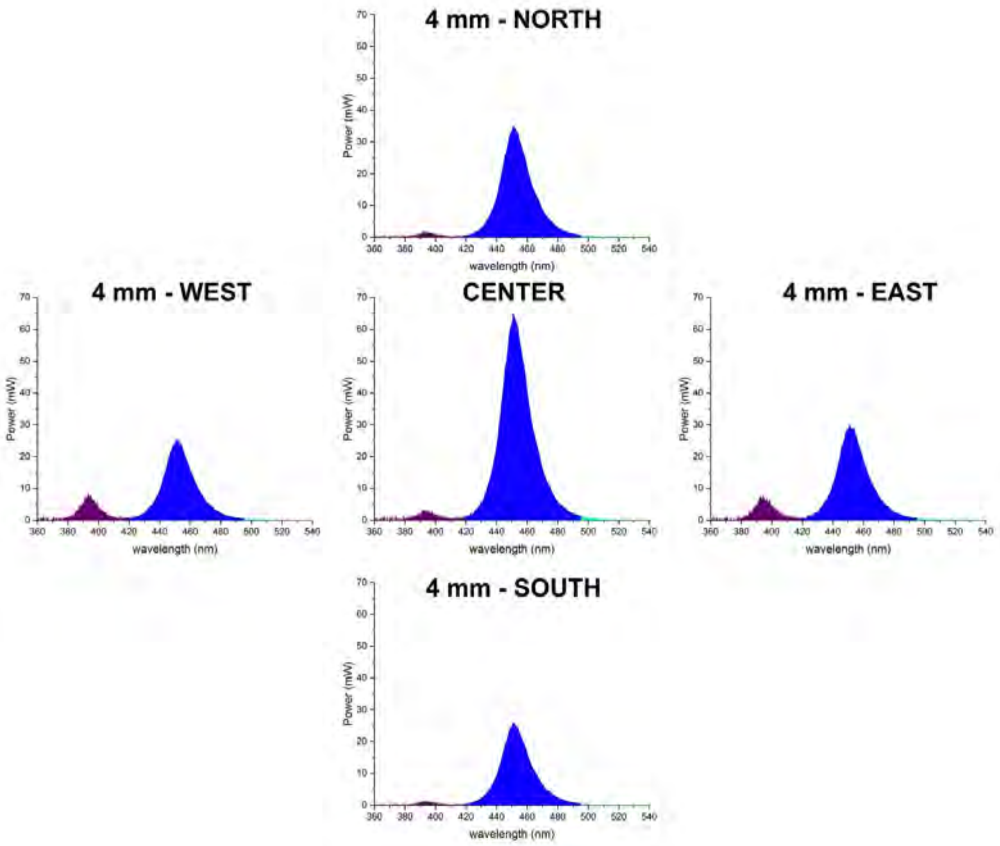

Figure 3. Spectral radiant power (mW/nm) of the broad spectrum LED at 1 mm distance according to the CENTER and 4 mm distant from the CENTER in the NORTH-SOUTH and WEST-EAST directions.

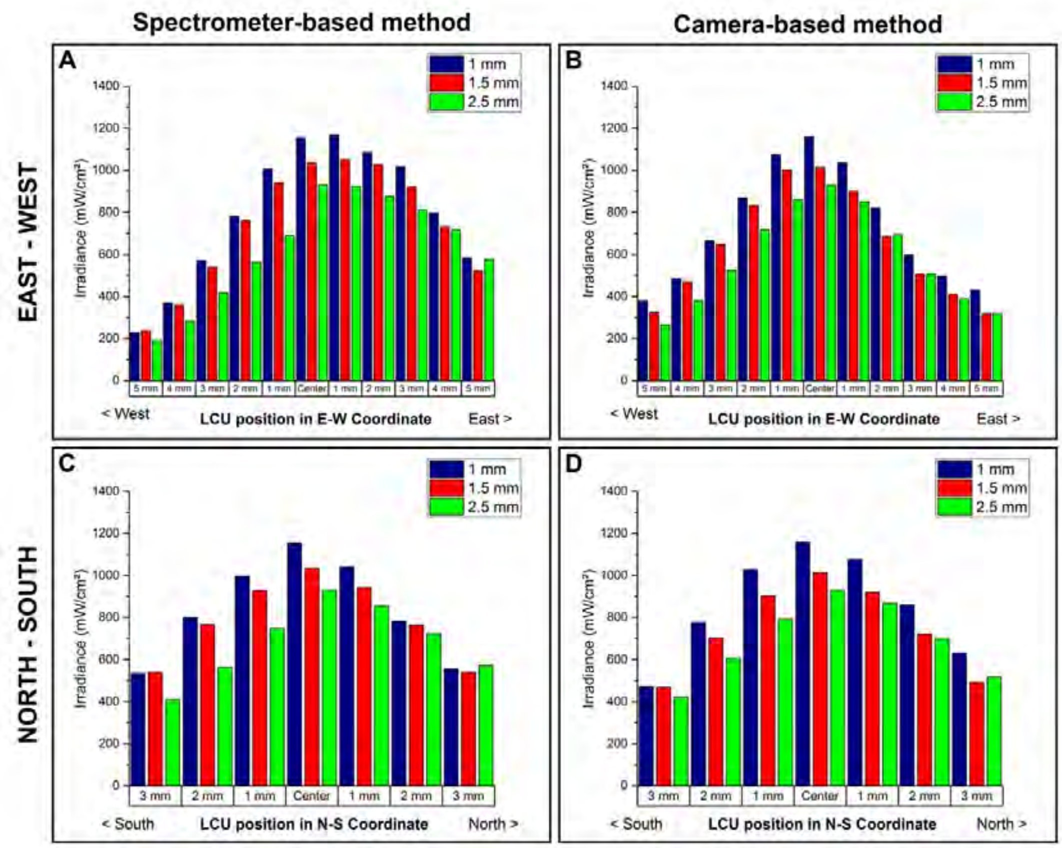

Figure 4. Irradiation measured at 1, 1.5, 2.5 mm distance from the light exiting window as a function of the offset in mm from the center position in the East-West and North-South direction using the spectrometer-based and the camera-based methods.

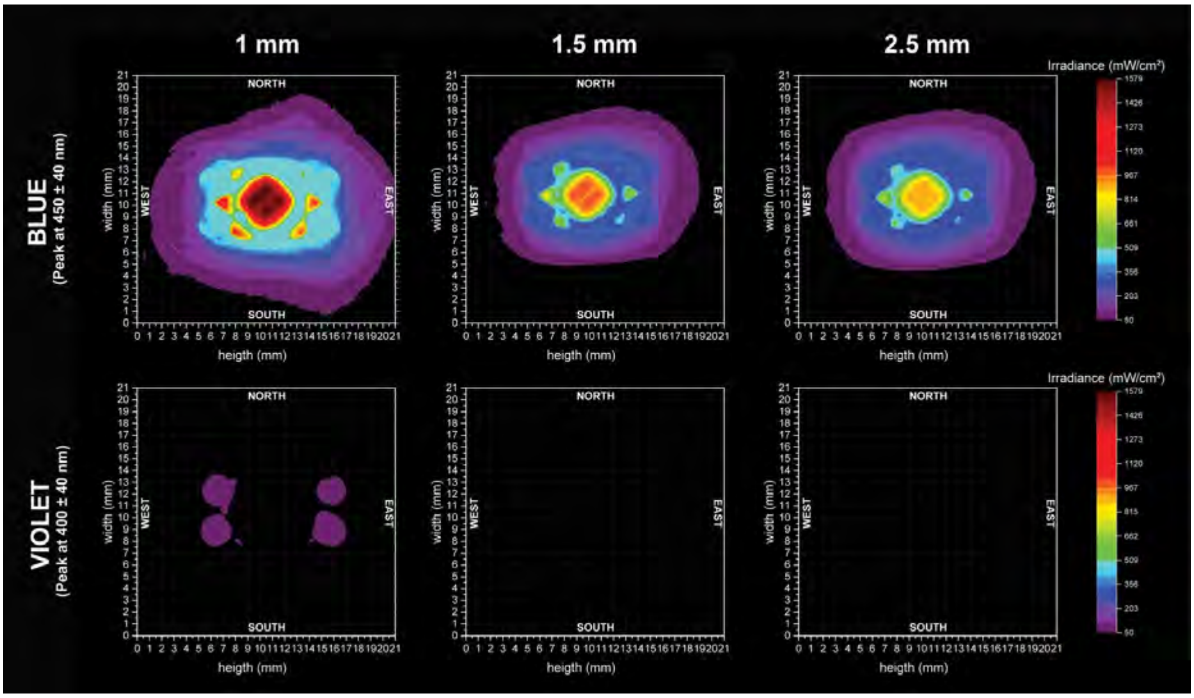

Figure 5. Beam profile images using the camera-based beam profiler method for the blue and violet wavelength ranges at 1, 1.5, 2.5 mm distance from the light tip.

Table 1. Slope of the decrease in irradiance in mW/cm²/mm with respect to the vertical distance of the geometric center of LCU and the NORTH, SOUTH, WEST and EAST directions using the spectrometer-based method or the camera-based method.

	1 mm		1.5 mm		2 mm	
	Spectrometer-based method	Camera-based method	Spectrometer-based method	Camera-based method	Spectrometer-based method	Camera-based method
NORTH	-232	-231	-195	-183	-169	-171
SOUTH	-244	-180	-201	-176	-142	-141
WEST	-173	-167	-171	-148	-100	-142
EAST	-197	-156	-181	-146	-127	-132

light as shown in Fig. 3. In Figure 1 the position of the LEDs in the head of the light is clearly visible. Using the beam profiler and different filters the center LED was identified to emit light blue light (420 – 495 nm) with a peak emission at 450 nm with a high intensity (1579 mW/cm²) and the four LEDs in the "corners" emitting violet light (380 – 420 nm) with a peak emission at 390 nm, confirming measurements on other LCUs [23,27]. Furthermore it was noticed that the irradiance from the violet LEDs was quite low (102 mW/cm²) and localized to the corners only. This discrepancy in the blue and violet light emission could be attributed to the type of the LED chip used to build the LCU. Despite the fact that the majority of LED chips are violet, they appear to be a dual in-line package (DIP) LED type, which have much lower energy efficiency than the blue light chip that appears to be a chip on-board (COB) LED type, which is considered a high-powered LED chip and the most recent development in LED LCUs. But, the fact is that "alternative" photoinitiators such as TPO or Ivocerin that have been used in commercial formulations are known as high reactive photoinitiators because they usually have higher molar extinction coefficient than CQ. This means that these photoinitiators absorb light more efficiently than CQ at their peak wavelength absorptions. Moreover, these photoinitiators form more free radicals (two or more) that have higher nucleophilicity and electron resonance than the one amino radical formed by the CQ-amine electron donor/hydrogen abstraction reaction. Thus, despite the less amount of violet light being emitted by broad spectrum LCUs, the initiation of the polymerization is effective enough to keep the physical and chemical properties of RBC containing "alternative" photoinitiators. However, it is important to bear in mind that broad spectrum LCUs typically have a ratio of 66 to 86 % of blue light emission and 14 to 34 % of violet light emission from the total spectral radiant power emitted [33] by the LCU. However, the LCU used in this study had 94% of blue light emission and 6% of violet light emission and further investigation should be performed to check if the LCU used in this study would efficiently cure RBC containing "alternative" photoinitiators. Therefore, it was decided that the impact on polymerization of these violet emitting LEDs was low and for further considerations we concentrated on the blue light.

In the present study, the LCU was laterally moved in a controlled way in the x- and y-direction of a coordinated system. This was to simulate in a reproducible way operator errors in light curing, which have a deleterious effect on the light energy administered to a restoration [33]. With a homogeneous beam profile, as long as a restoration is smaller than the diameter of the light exciting window of the LCU slight positioning errors may result only in minimal decrease of exciting irradiation if any at all. However, with an LCU that has a centered beam profile as the one of the Ascent OL5 used in the present study, the positioning even within the confines of the light exiting window has significant effects on the exciting irradiation, as can be seen in Fig. 4, where a marked decrease in irradiation is noticed when the LCU is moved in the X-Y direction.

The first null hypothesis that the irradiation would be at the same level all over the irradiated surface was rejected, since with both methods to characterize the LCU significant differences in local irradiance were found. In this study beam inhomogeneity could be shown as other researchers have done with different methods [25-28]. The second null hypothesis could be accepted, since the slopes of the decrease (in absolute numbers) were quite similar (Table 1). It is known that the irradiance a target surface received is a function of the exposure distance [25,26]. This is also visible in Figs. 3 and 5 confirming the results of others [25,26]. Furthermore, in Figs. 3 and 5 the irradiance dropped significantly from the center to the periphery in all measured directions ("East"-"West" and "North"-"South"). Looking at the absolute numbers of the slopes, the farther away from the LCU light exciting windows the smaller the numbers are, which means that the inhomogeneity decreases.

With controlled lateral movements, the inhomogeneity of the beam could be roughly reproduced with the spectrometer. The same could be shown with the beam profiler emulating a cosine corrector light collector with a diameter of 3.9 mm, which limits the precision. It is suggested to use a smaller cosine corrector diameter for future measurements. With the methods used, area specific mean irradiations could be shown. Therefore, one has to rely on the known minimal irradiance needed to cure a specific resin-based material in order to assess the performance of a given LCU/RBC combination.

The differences between the spectrometer-based vs camera-based beam profile methods are basically related to the resolution and accuracy of irradiance detection. Michaud et al. [29] used a laboratory grade integrating sphere spectrometer system to measure the irradiation and emission spectra of LCUs. Combined with a beam profiler camera they recorded the localized irradiance across the face of the light tip. The irradiation calibrated beam profile was then divided into 45 squares of 1 mm^2 each, thus being able to give more detailed beam analysis than it was possible with the method in the present paper. The beam inhomogeneity was additionally confirmed by micro hardness analysis [35].

Although the camera-based method can show higher resolution in mm^2 than the spectrometer-based method, the quantitative measurement of the irradiance using the spectrometer-based method seems to be more accurate, because the spectrometer-based method captures light directly from the light output tip, which is not the case for camera-based methods. Camera-based beam profilers are rarely able to give a direct measurement of the total irradiance of an LCU light beam. First, the LCU light beam passes through a long chain of attenuation so that the camera-sensor does not see the total power of the beam directly. Since this attenuation is put in place so as to get the energy down to the level of the camera sensor, it is not practical to calibrate each element of attenuation. Thus, the irradiance values that get into the camera are relative to the total power of the LCU light beam. Secondly, cameras do not have uniform wavelength absorption [36]. Therefore, they would have a different calibration factor for every wavelength of the LCU that is used. It would be impractical to attempt to calibrate the camera as a function of wavelength. So, after correcting for the power loss, the total irradiance energy measured by the spectrometer can then be entered into the software of the beam analysis instruments. From then on, the camera can give a readout of the total power or energy across the entire two-dimensional light beam distribution.

For the clinical application, the findings of the present study mean that even with a properly positioned LCU, peripheral areas would get much less irradiation. Even small positioning deviations would aggravate this fact, e.g. looking at Fig. 4 one can see that a 1.5 mm positioning deviation in the "WEST" direction would yield approximately 50% of the maximal possible irradiation. At a distance of 2.5 mm this effect is slightly less pronounced. As a clinical relevance of this study, it is important for the clinicians to understand that there are a lot of broad spectrum LCUs on the market, but not all of them might be really effective. And, it is important to be aware of the implications of bad quality broad spectrum LCUs on the quality of RBCs and thus on dental practice.

5. Conclusions

The analyzed LCU has an inhomogeneous beam profile, being the most intensive in the center and diminishing substantially towards the periphery.

The spectrometer-based method used was able to characterize an LCU which may be helpful among other parameters to make a selection for a specific LCU for clinical use.

Author contributions

JFR: Idea, experimental design, wrote the manuscript.
MGR: Performed standard camera-based beam profiles, contributed extensively to introduction and discussion.
CS: Performed data analysis, proofread the manuscript.
MMK: Performed spectrometer experiment. DCRSdeO: Contributed extensively to introduction and discussion.

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Questions

1. A beam profile is:

☐a. The change if irradiance as a function of the distance from the light curing unit light outputting window;
☐b. The 2D irradiance intensity plot of a light beam at a given location along the light beam output window;
☐c. Identical for all light curing units;
☐d. More homogeneous for broad band light curing units.

2. Which factor highly influencing the quality of a light cured resin composite is controlled by the dentist only?

☐a. The composition of the resin based composite;
☐b. Resin composite residues stuck to the light curing units light output window;
☐c. The geometry of the fiber bundle rod or the lens;
☐d. The correct positioning of the LCU on top of the RBC.

3. The study used the following method to characterize the light curing unit:

☐a. An Ulbricht sphere;
☐b. Micro hardness;
☐c. A spectrometer and a camera based beam profile method;
☐d. Degree of conversion of the resin based composite.

4. Which was the main outcome of the study?

☐a. No inhomogeneity of the beam profile could be found;
☐b. Both methods showed very similar inhomogeneities of the beam profile;
☐c. The beam profile inhomogeneity was the same regardless of the measuring distance;
☐d. The irradiance was higher at the periphery of the beam profile.