Stability and Reproducibility of Radiometric Properties of Light Curing Units (LCUs). Part II: LED LCUs

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The present work is the second part of a study on the stability and reproducibility of the energy and spectral emission of some light curing units (LCUs). In this part, Part II, LED LCUs were investigated. Results revealed that these devices presented high stability and reproducibility in terms of their spectral emission, with values of VAF (variance accounting for) coefficient calculated from the Cauchy–Schwarz inequality all close to 100%. With respect to energy stability, the LED LCUs presented energy stability except for the third-generation LED LCUs which have several LEDs. For these devices, the law of reciprocity was not fulfilled as irradiance was not constant over exposure time. This result should be taken into account both in works examining the polymerization kinetics of dental materials as well as when these LED LCUs are used in clinical practice.

Keywords: LED light curing units (LED LCUs), Radiometric properties, Spectral emission

INTRODUCTION

Development in light-emitting diodes (LEDs) in recent years has generated a significant growth market with completely new applications. Amongst which, blue LEDs have been proposed for curing light-activated dental materials^{1,2}. The spectral output of certain blue LEDs falls within the absorption spectrum of camphorquinone (CQ). This technology hence solves some problems inherent in dental light curing units (LCUs) based on halogen technology to polymerize oral biomaterials. The advantages³ include: (1) narrow spectrum eliminates the light filter system required by other technologies; (2) efficiently converts electricity into light with less heat generation, and subsequently less cooling is required; (3) long service life as it routinely functions on battery-charging cycles and battery life; and (4) little or no degradation over time as compared to the degradation of lamp, filter, and reflector with time in conventional halogen units. Further, it has been recently demonstrated that blue GaN LED has the potential to cure composite resins to the effect of exceeding the minimum requirements of ISO standards for depth of cure and tensile strength⁴. In view of the favourable results obtained, its performance can be considered clinically satisfactory⁵⁻⁷.

Nevertheless, its narrow emission width can be considered more as a disadvantage than an advantage. In fact, LED technology for dental curing uses a wavelength spectrum of 450 nm to 500 nm, which makes LED technology useless for any photoinitiator with absorption peaks below 450 nm — such as phenyl-propanedione, PPD, which has an absorption peak of 398 nm, Lucirin at 381 nm, or Irgacure with maximum peak at 370 nm⁸.

Since its introduction into the market, LED LCUs have evolved considerably, especially in terms of irradiance. The so-called first-generation LED LCUs presented an irradiance of 400 mW/cm² and a power output of 1 W. The so-called second generation reached 800 mW/cm² and 5 W, and the third generation, which emerged recently, exceeds 1.100 mW/cm² and 8 W. To date, study of dental LCUs has been approached from the analysis of their effectiveness to polymerize a certain dental material more than from the standpoint of evaluating their radiometric characteristics largely responsible for this effectiveness⁹⁻¹². Moreover, very frequently, these studies that compared LCUs or light curing protocols tended to focus on the different radiant exposure conditions or the final properties of the different materials, hence hampering the analysis and comparison of the results¹³. Consequently, it has been stated that LED LCUs polymerize more deeply than halogen lamps because their spectrum coincides with that of CQ, or that they are more efficient on an equal-energy basis¹⁴.

It is noteworthy that the polymerization of a composite depends not only on the amount of energy supplied, but also on the material's formulation¹⁵. In other words, results of these comparative studies cannot be indiscriminately and misleadingly extrapolated from one material to another. For this reason, if a study seeks to evaluate an LCU and compare one type of LCU *versus* another, the study needs to take into account the characteristics of the device itself and, specifically, its radiometric and spectral characteristics^{9,16}.

The aim of the present study, therefore, was to evaluate the stability and reproducibility of the radiometric properties of present LCUs, namely QHT

and LED LCUs. This work has been divided into two parts. In Part I, four QTH LCUs were investigated. In Part II, which was the present study, the focus was on LED LCUs. The first working hypothesis tested was that LED LCUs present spectral stability — that is, the shape of the emission curve as a function of exposure time does not vary. The second hypothesis tested was that LED LCUs present energy stability — that is, their total irradiance remains constant over exposure time.

MATERIALS AND METHODS

Characterization of the LCUs

In this study, seven commercial LED LCUs, provided by the manufacturers, were investigated. They were Bluephase (SN 1523676, Ivoclar Vivadent, Schaan, Liechtenstein), SmartLite PS and SmartLite IQ (SN AA00147 and 8878 respectively, Dentsply, Konstanz, Germany), MiniLED (SN 196-10470, cordless LED curing light, Acteon Group, Bordeaux, France), L.E. Demetron (SN 70048224, Demetron, Division of Kerr Corp., Danbury, CT, USA), UltraLume2 LED and UltraLume 5 LED (SN 004078 and 000114 respectively, Ultradent Products, South Jordan, UT, USA). Table 1 shows the technical characteristics specified by the manufacturers. Based on the irradiance infor-

mation given by each LED LCU's manufacturer and the respective output face dimensions, light emission flux was thereby calculated.

The emission spectrum of the light source, the spectral irradiance for each wavelength, and the total irradiance were determined using the same instrument as in Part I. The experimental conditions were the same as those in Part I, and likewise a total radiant exposure of 18 J/cm² was used.

Stability and reproducibility evaluation

To evaluate the stability and reproducibility of the spectral emissions of LED LCUs, correlation coefficients using Cauchy–Schwarz's inequality and VAF (variance accounting for) values were calculated. Intra-protocol and inter-protocol VAF values were then obtained as described in Part I.

To complete our stability and reproducibility analysis of the radiometric properties of each LCU, we also had to evaluate whether the total irradiance remained constant over exposure time according to this protocol. This study was conducted with three successive replicates of the same protocol. Based on the experimental data, a straight-line fit and regression coefficient for the three replicates of each light curing protocol were acquired and examined.

Table 1 Measured technical details of LCUs used in this study

LCU	Blue Phase	L.E.Demetron	MiniLED	Smart Lite I.Q.	Smart Lite PS	UltraLume 2LED	UltraLume 5LED
Light source	1 LED	4 LEDs	1 LED	1 LED	1 LED	2 LEDs	5 LEDs
Experimental peak emission wavelength (nm)	452	452	452	456	456	448	456 400
Manufacturer light emission flux (mW)	553	293	552	511	455	561	918
Experimental light emission flux (mW)	555	379	669	995	508	1594	993
Output-face light guide tip or window (mm)	8	6.43	7.5	8.5	8	6.43	6.43
Irradiance (manufacturer) (mW/cm ²)	1100	800	1250	900	950	>550	>900
Irradiance (experimental) (mW/cm ²)	1104	1440	1514	1753	1010	1561	973
Irradiance time (s)	16	23	14	20s	19	33	20
Total radiant exposure (manufacturer) (J/cm ²)	17.6	18.4	17.5	18	18	18.2	18
Total radiant exposure (experimental) (J/cm ²)	17.7	26.8	21.2	35.1	19.2	51.5	19.5

RESULTS

Table 1 shows the experimental values of the spectral and radiometric characteristics of each LED LCU examined in the present study: peak emission, light emission flux, total irradiance (mean value of three measurements), and total radiant exposure. As in Part I, the uncertainty that accompanied all the experimental measurements of irradiance was 6%.

Figure 1 shows the spectral irradiances of the seven LED LCUs used in this study. The thick solid

line denotes the absorption spectrum of CQ (in arbitrary units). It is worth noting that, as reflected in Fig. 1, UltraLume5 LED exhibited two emission peaks at 400 and 456 nm, given that it had two different types of LEDs.

Table 2 shows the maximum and minimum intra-protocol and inter-protocol VAF values for each of the LCUs. Maximum intra-protocol VAF value was 99.99%. The most unfavourable intra-protocol VAF value was 97.37%, obtained for the first replicate of the protocol corresponding to UltraLume5

Fig. 1 Spectral irradiances of the LED LCUs and the absorption spectrum of camphorquinone (in arbitrary unit).

Table 2 Maximum and minimum intra-protocol and inter-protocol VAF values of each LCU

LCU	Replicates	VAF intra-protocol	VAF inter-protocol
		Maximum-Minimum	Maximum-Minimum
Blue Phase	1	99.99%–99.85%	99.99%–99.95%
	2	99.99%–99.84%	
	3	99.99%–99.82%	
L.E. Demetron	1	99.99%–99.42%	99.94%–99.35%
	2	99.99%–99.04%	
	3	99.99%–99.54%	
MiniLed	1	99.99%–99.76%	99.89%–99.56%
	2	99.99%–99.80%	
	3	99.99%–99.81%	
SmartLite I. Q.	1	99.99%–99.94%	99.99%–99.96%
	2	99.99%–99.93%	
	3	99.99%–99.90%	
SmartLite S. P.	1	99.99%–99.80%	99.98%–99.70%
	2	99.99%–99.80%	
	3	99.99%–99.84%	
UltraLume 2LED	1	99.99%–99.73%	99.99%–99.82%
	2	99.99%–99.97%	
	3	99.99%–99.73%	
UltraLume 5LED	1	99.99%–97.37%	99.96%–97.73%
	2	99.99%–99.65%	
	3	99.99%–99.93%	

LED. It warrants highlighting that 97.73% of UltraLume5 LED was an exceptional case, as the rest of the minimum values exceeded 99.00%.

With regard to inter-protocol VAF values, it should also be emphasised that the maximum VAF value was 99.99%, while the minimum was 97.73%

in the case of UltraLume5 LED. As with the intra-protocol VAF value, the latter result was an exceptional case as all the other minimum values exceeded 99.00%.

Figures 2a–e show the total irradiance values for Bluephase, MiniLED, SmartLite PS, SmartLite

(2a)

(2d)

(2b)

(2e)

(2c)

Fig. 2 Total irradiance values of Bluephase (a), MiniLED (b), SmartLite IQ (c), SmartLite PS (d), and UltraLume2 LED (e), as well as straight lines drawn from manufacturers' and experimental values. The intervals represent instrumental errors.

(3a)

(4a)

(3b)

(4b)

(3c)

(4c)

Fig. 3 Total irradiance values of L.E. Demetron as well as straight lines drawn from manufacturer's values and experimental values for the three replicates. The intervals represent instrumental errors.

Fig. 4 Total irradiance values of UltraLume5 LED as well as straight lines drawn from manufacturer's values and experimental values for the three replicates. The intervals represent instrumental errors.

IQ, and UltraLume2 LED LCUs, whereby temporal stability could be evaluated. Each LCU was represented by only one of the three replicates, given the similarity of the three results for each of these five LCUs. In these figures were also shown the equations of the theoretical straight lines and the manufacturers' straight lines.

Figures 3a–c and 4a–c show the results of the three replicates performed for L.E. Demetron and UltraLume5 LED LCUs respectively. With these two devices, the three replicates performed are shown because of the divergence among them. As in Figs. 2a–e, equations of the corresponding theoretical straight lines for each of the three measurements and the manufacturers' straight lines are also shown.

DISCUSSION

In the present study, all the LCUs examined yielded a maximum intra-protocol VAF value of 99.99%, with minimum values close to the maximum and statistically very high, indicating that the LCUs, in terms of spectral emission, presented high stability like QTH LCUs.

With respect to inter-protocol VAF values (fourth column of Table 2), conclusions similar to those for intra-protocol could be drawn. It was only in the case of UltraLume5 LED LCU, where one replicate registered a spectral emission curve that differed slightly from the other two replicates. Despite being so, the differences were not great and thus the corresponding inter-protocol VAF value was 97.73%. As indicated in Part I of the work with QTH LCUs, the inter-protocol values obtained herein indicated the high reproducibility of the LED LCUs with regard to their spectral emission.

In light of the VAF results obtained, it could be affirmed that the LED LCUs studied exhibited stability and reproducibility in terms of spectral emission. On this ground, the first hypothesis of our research was verified and accepted.

With LED LCUs, spectral stability is even more important than with QTH LCUs. Owing to a narrower spectral width, a small variation in emission could translate into a withdrawal from the absorption peak of the photoinitiator. However, with QTH LCUs, the spectral width is great and the problem is not as critical. In summary, we can assess whether the current light curing units guarantee that during the time corresponding to a clinical protocol or to protocols close together in time, the spectral range and peak remain constant.

With respect to energy stability, concordance was found only with Bluephase (difference < 6%) after comparing the experimental irradiance values with the theoretical ones provided by the manufacturers.

For SmartLite PS, the difference was 6%. For most of the LCUs, this difference was far greater — which also occurred in Part I for QTH LCUs. On this note, the results of SmartLite IQ and UltraLume2 LED should in particular be highlighted as their experimental irradiance values exceeded the manufacturers' values by 190% and 280% respectively. These differences were of the order of magnitude of those found for QTH LCUs (175% and 230% for Bluephase and Spectrum 800 respectively).

Exposure time of each LCU was calculated from the irradiance value given by the respective manufacturer. Consequently, the quantity of energy that the device provided experimentally was far higher than the amount presumed to be applied following an established protocol, as reflected in the last two rows of Table 1 (18 J/cm² against 35.1 J/cm² for SmartLite IQ or 18.2 J/cm² against 51.5 J/cm² for UltraLume2 LED). These high amounts of energy bore practical implications for the polymerization of dental composites and the biological effects of visible light.

First, it has been unequivocally demonstrated that both irradiance and radiant exposure significantly impact the polymerization kinetics of light-cured resin composites¹⁷, as well as the mechanical properties and cure characteristics of the resulting polymer¹⁸. Next, there is also a prevailing concern about the biological effects of short-wavelength light (within the visible spectrum). To date, it has been affirmed that it is not harmless — whereby effects at the cellular level are dose- and wavelength-dependent¹⁹. Nonetheless, given the meagre information currently available on this subject, future research should be undertaken to clarify these biological effects.

Concerning the discrepancies observed between the experimental irradiance values and those given by the manufacturers, it has been reported in Part I that these discrepancies might be attributed to the different radiometric devices reporting different irradiance values, especially with dental radiometers^{20,21}. On this note, our results for LED LCUs from the present study further supported a recent recommendation⁹ on the need for accurate measurement and precise reporting of radiometric quantities employed in the photoactivation process.

Figures 2a–e show the results for LED LCUs which had very similar values for the three replicates of the same protocol: Bluephase, MiniLED, SmartLite PS, SmartLite IQ, and UltraLume2 LED. As in Part I, the regression coefficient values indicated that the experimental values did not closely fit a straight line, although they differed from one LCU to another. Furthermore, some devices presented an initial value below the mean (Bluephase and SmartLite PS), while others presented an initial value above the mean

(MiniLED and UltraLume2 LED).

With MiniLED, SmartLite PS, SmartLite IQ, and UltraLume2 LED LCUs, instrumental error could be taken into account such that a straight line could be drawn with a zero slope and ordinate at the origin within the uncertainty values of the means of these three devices. Thus, these four LCUs could be considered energetically stable over time after taking into account their associated error. However, even if they were deemed energetically stable as indicated above, the negative slope showed a fall in irradiance value over time. Electronically, the decline was due to heating up of proton-neutron pairing by high-intensity LEDs and which is generally enclosed in a very small capsule with a refrigeration system consisting of a small ventilator. Nevertheless, this slight descent was not found for SmartLite IQ LCU. With this device, the values fluctuated without a definite trend.

If the first measurement were to be eliminated, as was done in Part I for some halogen LCUs, the straight line (*i.e.*, the regression line) for Bluephase, for instance, was $y = -3.01(1.40)x + 1128.22(13.90)$ and $p < 0.0001$. As shown in Fig. 5, when the initial value was disregarded considering its associated error, the device showed good energy stability over time. Nevertheless, with LED LCUs, it was concluded that the initial irradiance value is critical in LCU stability, as was the case with QTH LCUs in Part I of the work.

For L.E. Demetron (Figs. 3a–c) and UltraLume5 LED (Figs. 4a–c) LCUs, they did not show a similar irradiance pattern over time for the three replicates. Based on the results for Parts I and II of our work, QTH LCUs as well as LED LCUs showed increasing and decreasing irradiance trends over time, and where stability could be considered acceptable if the first irradiance value were eliminated. However, for these two LCUs, their irradiance values over exposure time varied in an apparently random way. Furthermore, for each of the three replicates pertaining to the same protocol, there was no best-fit straight line. This occurred despite taking into account the instrumental errors or eliminating the initial irradiance value, hence showing the absence of energy stability for these two LCUs.

It should be highlighted that these two LCUs had four and five LEDs against the rest of the LED LCUs, which had only one LED and two for UltraLume2 LED. Indeed, poor energy stability is associated with LCUs that have more than one LED, since they are encapsulated or integrated. In view of these unfavourable energy stability results, the second hypothesis of the present research was rejected. In other words, the most modern LCUs presented the worst results in terms of energy stability of all the devices studied, including QTH and LED LCUs

Fig. 5 Total irradiance values of Bluephase with the initial value removed and a new best-fit straight line. The intervals represent instrumental errors.

which have a single LED.

The most probable reason is that there are no circuits to provide a stable electrical intensity. Consequently, tension (and therefore the current) varies and hence the light energy, as the latter is proportional to the tension or current intensity. In the case of LCUs with several LEDs, energy variability is adversely exacerbated as variation in light is multiplied by the number of LEDs. In view of this result, it would be advisable to review the electrical and electronic design of these new LCUs for the correct application of the law of reciprocity between irradiance and irradiation time and for adequate polymerization of dental resin composites.

The lack of energy stability detected in LED LCUs with several LEDs revealed that there was no guarantee that the irradiation time proposed in a protocol would surely and sufficiently provide the total radiant exposure required for the correct polymerization. This result should be taken into account both in works investigating the polymerization kinetics of dental materials as well as when these devices are employed in clinical practice.

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