Stability and Reproducibility of Radiometric Properties of Light Curing Units (LCUs). Part I: QTH LCUs

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The present study, divided into two parts, analyses the stability and reproducibility of the spectral and energy emission of the present light-curing units (LCUs), quartz tungsten halogen (QTH) and light-emitting diodes (LEDs). In part I, QTH LCUs were studied. The results showed that the QTH LCUs studied presented high stability and reproducibility in terms of their spectral emission with VAF (variance accounting for) values from the Cauchy-Schwarz inequality, all close to 100%. With respect to the energy stability, the QTH LCUs studied can be considered stable under practical clinical conditions, although for some devices the initial irradiance value is critical. This result should be taken into account in those works which is researched in polymerization kinetics of dental materials as well as in clinical practice.

Keywords: Quartz tungsten halogen light-curing unit (QTH LCUs), Radiometric properties, Spectral emission.

INTRODUCTION

Photoactivation is routinely used in dentistry to start the hardening of clinical materials, such as tooth-coloured restorative materials or composites. These materials are of broad clinical use, although they present certain problems that are usually related to the volumetric reduction that they undergo during the polymerization reaction. In recent years, numerous research lines have been developed with the aim of finding alternatives to minimize the effects of this phenomenon. In this sense, one of the most active is related to light-curing unit (LCU)1-5, specially after alternatives to conventional quartz tungsten halogen (QTH) were introduced into the dental market. Among these are the so-called “high-intensity QTH”, the lamps of plasma arc and light-emitting diodes (LED). At the same time, new photoactivation protocols were proposed, differing from the conventional one (400 mW/cm² for 40 s) and were generally meant to shorten clinical work time6.

This diversity of LCUs and of protocols has spurred the publication of numerous studies. For example, light sources have been compared on the basis of their effectiveness in photoactivating materials, by the evaluation of their final physical characteristics (hardness, wear resistance, elastic module, etc.)1,5,7-11. Protocols have been evaluated in terms of their capacity to diminish the microfiltration and improve the performance of the adhesive interphase 12,13, their ability to increase the depth of the curing process14,15 or to improve polymerization kinetics1,16. These works, in short, show the influence of the LCUs on the clinical behaviour of the material.

Briefly, the radiant incidence or irradiance (E), in the appropriate wavelength range, and the irradiation time (t) are crucial to the completeness of polymerization, and determine the development of the physical and mechanical properties of resin composite restorative materials. Correctly measuring radiometric quantities and reporting radiometric data are essential for a more complete understanding of the requirements and polymerization kinetics of dental resin composites17. The particular importance is not only their spectral emission and irradiance, or combinations of these properties but also the stability of these properties over time, an aspect not usually taken into account in most studies on dental LCUs.

For the study of the stability of the radiometric properties described for the LCUs, the spectral-emission curve must be firstly studied. A lamp is considered spectrally stable when it maintains the shape of spectral emission constant over time, in our case during the clinical protocol, and this form is systematically reproducible by a device18,19. Secondly, an evaluation must be made as to whether the irradiance value remains constant during the protocol time.

Given the complexity of polymerization kinetics, a simple reciprocity between E and t20, will indicate the appropriate irradiation time, if we take into account the wide range of irradiance shown by the present LCUs. The implication of law of reciprocity is that K=E*t, the total radiant exposure (mJ/cm² or J/m²) required, is constant over time. This law between the irradiance and the irradiation time implies that the first remains constant over irradiation time. However, there are no works available where, in an implicit and systematic way, the variation of the irradiance is studied over the time stipulated in the protocol or where it is determined whether the irradiance remains invariant in different exposures.

The aim of the present study was to evaluate the stability and reproducibility of the most relevant radiometric properties of present dental LCUs, QTH
and LED. This study is divided in two parts. In part I, the first research hypothesis tested was that high-intensity QTH LCUs present spectral stability — that is, the shape of the emission curve during the irradiation time does not vary. The second research hypothesis tested was high-intensity QTH LCUs present energy stability — that is, their total irradiance remains constant over emission time.

MATERIALS AND METHODS

Characterization of the LCUs

In this study, four QHT LCUs that were provided by the manufacturer were used: Astralis 10 (SN 011473 Ivoclar-Vivadent, Schaan, Liechtenstein), BlueLight (SN 045DA061, Mectron, Carasco, Italy), Spectrum 800 (SN 9169, Dentsply, Konstanz, Germany) and Swiss Master Light (SN BB00058, Electro Medical Systems, Nyon, Switzerland). For the measurements, in all cases, we selected the mode in which the device provided the maximum irradiance value possible. Table 1 shows the technical characteristics specified by the manufacturers. From the irradiance specified and the output-face guide tip, the emission flux was calculated, as this information is not usually provided in the technical specifications.

The emission spectrum of the source, the irradiance for each wavelength (spectral irradiance), and the total irradiance were determined using a SpectraScan PR-650 new-generation Spectroradiometer from Photo Research Inc. (Chatsworth, CA USA). Its spectral range was 380-780nm, bandwidth resolution 8nm, and exactitude ±2nm with a 2% measurement error. The irradiance was measured with a CR-600 cosine diffusor. Given that the units needed electrical connections, they were connected to an electronic current voltage stabilizer (model B-117, TRQ s.l. Vinarós, Spain) in order to avoid electric fluctuations of the commercial electrical lines.

Taking into account that the total radiant exposure necessary for adequate polymerization of the hybrid composites of close to 18 J/cm² for 2 mm in thickness[1], this value was taken as the reference so that, beginning with the irradiance value listed by the manufacturer, the exposure time was selected, Table 1, by using each LCU in the study.

For the study, three successive replicates were taken of the protocol established for each of the LCUs.

Evaluation of stability and reproducibility

To evaluate the stability and the reproducibility of the spectral emission of each LCU, we calculated the VAF (variance accounting for) coefficient with

<table>
<thead>
<tr>
<th>Light source</th>
<th>Astralis 10</th>
<th>BlueLight</th>
<th>Spectrum 800</th>
<th>SwissMaster Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental peak emission wavelength (nm)</td>
<td>472 Halogen bulb</td>
<td>496 Halogen bulb</td>
<td>488 Halogen bulb</td>
<td>500 Halogen bulb</td>
</tr>
<tr>
<td>Manufacturer light emission flux (mW)</td>
<td>603</td>
<td>402</td>
<td>402</td>
<td>2592</td>
</tr>
<tr>
<td>Experimental light emission flux (mW)</td>
<td>690</td>
<td>707</td>
<td>943</td>
<td>2851</td>
</tr>
<tr>
<td>Output-face light guide tip (mm)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Irradiance (manufacturer) (mW/cm²)</td>
<td>1200</td>
<td>&gt;800</td>
<td>800</td>
<td>3000</td>
</tr>
<tr>
<td>Irradiance (experimental) (mW/cm²)</td>
<td>1373</td>
<td>1407</td>
<td>1876</td>
<td>2727</td>
</tr>
<tr>
<td>Irradiance time (s)</td>
<td>15</td>
<td>23</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>Total radiant exposure (manufacturer) (J/cm²)</td>
<td>18</td>
<td>18.4</td>
<td>18.4</td>
<td>18</td>
</tr>
<tr>
<td>Total radiant exposure (experimental) (J/cm²)</td>
<td>20.6</td>
<td>32.4</td>
<td>43.1</td>
<td>16.4</td>
</tr>
</tbody>
</table>
Cauchy-Schwarz’s inequality via the expression

\[ VAF = \left( \frac{\sum_{k=1}^{780} a_k b_k}{\left( \sum_{k=1}^{780} a_k^2 \right)^{1/2} \left( \sum_{k=1}^{780} b_k^2 \right)^{1/2}} \right)^2 \]  

(1)

where \( a_k \) is the value of each irradiance (for each wavelength) and \( b_k \) is the equivalent for another measurement. The closer this coefficient gets to unity (100%), the more similar the two curves become. This coefficient is related to the confidence level of each normal distribution.

In our study, we calculated the value of the VAF coefficient for the irradiance values found over the exposure time of the same protocol, VAF intra-protocol, and between the irradiance values of the three replicates made for the same protocol, VAF inter-protocol.

For the calculation of the VAF intra-protocol coefficient, during the exposure time of the protocol a series of successive irradiation measurements were taken and, in each one, the spectral emission was recorded and all the measurements made were compared. In this case, the VAF intra-protocol value indicates whether the shape of the curve of spectral emission of the LCU is constant (remains steady over exposure time) within the same protocol. Also, for the calculation of the VAF inter-protocol coefficient, the spectral-emission values of the three measurements of the same protocol were compared. In this case, the VAF inter-protocol indicates whether the shape of the curve of spectral emissions remained constant in successive measurements of the protocol in time.

If the results of VAF intra-protocol and inter-protocol are close to 100%, the spectral emission of the LCU can be considered stable and reproducible. We calculated both coefficients for each LCU.

To complete our analysis of stability and reproducibility of radiometric properties of each LCU, we also had to evaluate whether the total irradiance remains constant over exposure time corresponding to the protocol. This study was made for each of the three successive replicates of the same protocol. If the total irradiance is constant in time, the measurements should fit a straightline of null slope (\( a=0 \)). Also, so that the total radiant exposure supplied by the LCU was close to 18J/cm², the ordinate at the origin, \( b \), should coincide with the total irradiance given by the manufacturer. That is, if we take into account both conditions, the fit to a straightline should be \( y = b \), where \( b \) is the total irradiance provided by the manufacturer. In addition, this should be repeated in each of the three measurements of the same protocol. For this reason, from the experimental data, we calculated the straightline with the best fit and the regression coefficient.

RESULTS

Table 1 lists also the experimental values of each QTH LCUs studied: the emission peak, total irradiance (mean of three measurements), total radiant exposure, and light-emission flux. As the experimental value given in Table 1 is an average of the mean values of the three measurements, and as each of these had an associated uncertainty of 2%, the error that accompanied all the experimental measurements of Table 1 was 6%.

Figure 1 shows, with different lines, the spectral
Table 2  Values of the VAF of each

<table>
<thead>
<tr>
<th>LCU</th>
<th>Replicates</th>
<th>VAF intra-protocol</th>
<th>VAF inter-protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum-Minimum</td>
<td>Maximum-Minimum</td>
</tr>
<tr>
<td>Astralis 10</td>
<td></td>
<td>99.99% - 99.98%</td>
<td>99.99% - 99.98%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>99.99% - 99.93%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.99% - 99.97%</td>
<td></td>
</tr>
<tr>
<td>BlueLight</td>
<td></td>
<td>99.94% - 99.54%</td>
<td>99.99% - 99.95%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2</td>
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<td>3</td>
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<tr>
<td></td>
<td>2</td>
<td>99.99% - 99.99%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.99% - 99.95%</td>
<td></td>
</tr>
<tr>
<td>Spectrum 800</td>
<td></td>
<td>99.99% - 99.94%</td>
<td>99.97% - 99.95%</td>
</tr>
<tr>
<td></td>
<td>1</td>
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<tr>
<td></td>
<td>2</td>
<td>99.99% - 99.98%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.99% - 99.89%</td>
<td></td>
</tr>
<tr>
<td>SwissMaster Light</td>
<td></td>
<td>99.99% - 99.76%</td>
<td>99.88% - 99.87%</td>
</tr>
<tr>
<td></td>
<td>1</td>
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<tr>
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<tr>
<td></td>
<td>2</td>
<td>99.99% - 99.78%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.99% - 99.81%</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2  Total irradiance values of Astralis 10 (2a), BlueLight (2b), Spectrum 800 (2c) and Swiss Master Light (2d) and the manufacturer’s and experimental straightlines. The intervals represent the instrumental error.
irradiance of the four LCUs used in our study. The thick continuous line shows the absorption spectrum of the camphorquinone (CQ), in arbitrary units.

Table 2 shows the minimum and maximum values of the VAF intra-protocol and inter-protocol calculated for each LCU. According to the results, the maximum VAF intra-protocol for each unit was 99.99% and the most unfavourable case was 99.33% for second replicate of the LCU Astralis 10. With respect to the VAF inter-protocol values, as in the previous case, the maximum VAF inter-protocol was 99.99% while the minimum value was 99.87% (Swiss-Master Light).

In terms of temporal energy stability of the LCUs, Figures 2a-d show, for each LCU, the irradiance values found over exposure time of a protocol. Only one of the three replicates of the same protocol of each LCU is represented, given the similarity of the results. Also, the equations are presented for the theoretic straightlines calculated (slope, ordinate at the origin, and the squared regression coefficient) and the manufacturer’s straightline.

DISCUSSION

As commented above, one LCU has spectral stability and reproducibility when the shape of the curve of the light spectrum emitted is constant not only during the time taken up by one photoactivation cycle (intra-protocol) but also by one cycle to the other (inter-protocol). Within the same protocol, third column of Table 2, all the LCUs studied showed a maximum VAF intra-protocol of 99.99%, and all minimum values close to the maximum value and statistically very high, permitting us to affirm that the units studied present high stability in terms of spectral emission.

Notably, the fact that the shape of the spectral-emission curves was very similar (VAF intra-protocol close to 100%) does not mean that the total irradiance value was also constant over exposure time. For instance, Fig. 3 shows the spectral irradiance of each of the measurements made during the exposure time of Astralis 10 (VAF intra-protocol among 99.99%-99.98%). As can be seen, the shapes of the spectral-irradiance curves are practically identical, although for measurement 1 (broken line), the area is clearly smaller than the rest, implying a different total-irradiance value, but not the shape of the curve of the light spectrum emitted by LCU.

A detail should be emphasized in reference to the minimum VAF intra-protocol value. In the comparisons of measurements within the same protocol, when the measurements compared were close in time, the VAF values were nearly 100%. The most pronounced differences (minimum VAFs) were found between measurements far apart in time. This may signify that, although the overall spectral stability and, therefore, its reproducibility can be considered very good, the shape of the initial and final spectral-emission curves differed, but not significantly. It seems that the LCU needs a certain time to attain spectral stability, and, once having reached this point, the stability persisted in time almost perfectly. This phenomenon has repercussions, as we will discuss below, in the temporal stability of the total irra-

![Fig. 3 Spectral irradiance of Astralis 10 (first replicate).](image1)

![Fig. 4 Total irradiance values of Astralis 10 after discarding the initial irradiance value and the new straightline fit. The intervals represent the instrumental error.](image2)
diance.

With respect to the VAF inter-protocol values, fourth columns of Table 2, we can draw similar conclusions to those presented above, and even the minimum value found for the VAF inter-protocol was 99.87%, higher than the VAF intra-protocol minimum. This result indicates the high reproducibility that these devices present in terms of their spectral emission.

The efficiency of various visible LCUs used with CQ-containing composites was evaluated by Cook showing quantitatively the need for a good overlap between the emission of the LCUs and the absorption spectrum of CQ, as occurred in the devices studied (Fig. 1). Furthermore, given the VAF values calculated, we can state that the QTH LCUs studied present spectral stability and reproducibility in their spectral emission; it guarantees the photoactivation of CQ in the same wavelengths over the entire time period of the protocol and in different protocols. Thus, the first research hypothesis expressed in the Introduction is accepted.

The stability in emission should be established not only in relation to the emission spectrum but also in relation to the total quantity of light emitted — that is, the total irradiance remains constant over exposure time, corresponding to the clinical protocol. As commented above, if the total irradiance is constant in time, the measurements of the irradiance should fit a straight line of null slope \( (a=0) \). Also, for the total radiant exposure to be 18J/cm², the ordinate at the origin should be the total irradiance given by the manufacturer. For this, the experimental value of the total irradiance of the LCUs studied would to agree with that provided by the manufacturer, considering the instrumental error.

Fig. 2a—d, graphically represents the total irradiance values during the exposure time of each QTH studied. In all the devices, the values of the regression coefficient indicate that the experimental values, although differing from one LCU to another, do not fit a straight line. In addition, the ordinates at the origin do not coincide with the mean irradiance values determined experimentally, nor with those provided by the manufacturer. Furthermore, the slope, theoretically, should be null but, in no case does this occur. Consequently, in view of these results, we can state that, in principle, the irradiance value of the QTH LCUs does not agree the manufacturer’s indications (according to the value of the ordinate at the origin) nor is it constant over emission time (according to the non-null slope).

Nevertheless, some considerations are needed on this initial result. In the case of Astralis 10, if we discard the first measurement, we get a straight line with zero slope (including the error corresponding to the fit) with an ordinate value at the origin very close to that found experimentally. As an example, Fig. 4 shows the new straight line fit for one of the three measurements, the equation of which is \( y = (-0.7 \pm 1.1)x + (1375 \pm 14) \), with a p-value < 0.001. Comparable results were found with the two remaining replicates. With Swiss Master Light (Fig 2d), the results were similar and the new straight line fit for this LCU, is \( y = (-23 \pm 27)x + (3192 \pm 103) \), with a p-value<0.001.

Given the results for Astralis 10 and Swiss Master Light, we can conclude that the initial irradiance value may be critical in terms of the energy and temporal stability of the halogen lamps analyzed. This behavior does not appear in the case of BlueLight and Spectrum 800, as reflected in Fig. 2b-c. The two show contrary trends with respect to the previous ones — that is, the irradiance value diminished over the course of emission time. For BlueLight, as shown in Fig. 2b, the straight line had a slope close to zero (considering the adjustment error), a regression coefficient close to unity (p-value<0.001) and the ordinate at the origin near the values calculated in our laboratory when we considered the instrumental error associated with the experimental errors. Therefore, without the need to eliminate the initial measurement, this LCU displayed energy stability over time although the manufacturer’s irradiance and the experimental irradiance values were not identical.

In the case of Spectrum 800, Fig. 2c, the initial values were far higher than the rest, especially at the start of the measurements (measurement 1). Values gradually decreased to measurement 8 and from then on appeared to become quite stable. Despite taking the instrumental error into account, we could not find a straight line with a null slope that could demonstrate temporal stability in the emission.

Under these conditions, we consider that the second research hypothesis expressed in the Introduction section is partially supported.

From the clinical standpoint, it is important to evaluate whether the variations in output measurement over time obtained are clinically significant considering the influence of other factors — for example, the variation in distance to the specimen while hand holding the device. If we consider the initial measurements of the lamps Astralis 10, Spectrum 800, and Swiss Master Light, the standard deviations between the irradiance measurements over time of the first replicate of the protocol are: 5.07, 11.03, 69.77, and 10.05 for the lamps Astralis 10, Bluephase, Spectrum 800, and Swiss Master Light, respectively. Analogous results were found for the other two replicates. In all cases, the standard deviations found were lower than the corresponding 6% of the instrumental error and lower than the variations due to the difference in distance to the specimen while hand holding the device.
Nevertheless, it bears emphasizing that in terms of energy stability over time, in the QTH LCUs studied, there was no constant performance pattern, perhaps due to electrical causes. Thus, while Astralis 10 and Swiss Master Light LCUs reached a stable state of emission after the initial instants, which seems reasonable, the temporal evolution of the emission of Spectrum 800 is the reverse. This phenomenon could be related to an excessive passage of current through the electric circuit. This anomalous behaviour would also explain the fact that the irradiance emission of this LCU is 230% greater than indicated by the manufacturer. In this sense, we can verify that the differences between the total irradiance values found in our laboratory and those stated by the manufacturer (Table 1) were higher than the experimental error (6%) are notable. Except for the Swiss-Master Light, all were higher than those provided by the manufacturer. In specific, the cases of BlueLight and Spectrum 800 are especially noteworthy, with experimental total irradiance values exceeding manufacturer values by 175% and 230%, respectively, as pointed out above. Therefore the units provide a total radiant exposure far higher than the user might believe, with the corresponding consequences. For example, recently, it has been demonstrated that the polymerization-contraction force rate is linearly related to irradiance\(^{25}\), showing that variations in total irradiance can heavily influence the final performance of the material.

The discrepancies observed between the values of the experimental irradiance and the manufacturer’s reported values may be due, as indicated by some authors\(^{26,27}\), to the fact that different radiometric devices report different irradiance values, posing the need to undertake studies that enable the user to know, from a laboratory and from a clinician’s standpoint, the correct method of monitoring the output from the LCU. In this sense, our results support recent recommendations\(^{17}\) on the need for accurate measurement and precise reporting of radiometric quantities employed in the photoactivation process, in order to develop a more complete understanding of the curing kinetics.

Some authors\(^{29}\) using dental radiometers, have compared different LCUs by measuring microleakage, shear-bond strength, and surface hardness of a dental composite and have indicated the possibility that the contradictions found in the experimental results could be attributed to errors in measuring the irradiance. In agreement with our results, and as the final characteristics of the material depends not only on the quantity of energy applied but also on the variation of this energy over the protocol, only the adequate radiometric characterization of the QTH LCUs used enables accurate conclusions to be drawn over its influence in the kinetics of polymerization of photoactivated materials.

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**REFERENCES**

13) Cavalcante LMA, Peris AR, Amaral CM, Ambrosano,


15) Fan PL, Schumacher RM, Azzolin K, Geary R and Eichmiller FC. Curing-light intensity and depth of cure or resin-based composites tested according to international standards. JADA, 2002; 133: 429-434.


