TIME DEPENDENT ACCURACY OF DENTAL RADIOMETERS

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SUMMARY – Inadequate intensity of the polymerization light source can compromise the quality and longevity of dental composite restorations. In order to maintain optimal strength of polymerization devices, regular control of polymerization units is necessary. The aim of this study was to compare the accuracy of two radiometers in the measurement of light intensity of photopolymerization devices concerning the time point of measurement. Light intensity measurements of 16 halogen and 8 LED curing lights were performed using three different devices at the beginning as well as 10 and 40 seconds after the start of illumination. Two were handheld radiometers: Bluephase meter (BM) and Cure Rite (CR), while an integrating sphere (IS) represented the reference device. Data were statistically analyzed using Friedman's test and Wilcoxon signed-rank test ($p<0.05$). The values at the beginning and after 10 seconds measured by BM were significantly higher than the measurements by IS, whereas CR showed higher values after 10 and 40 seconds. Both commercial radiometers tended to overestimate the light intensity of LED and halogen curing units when compared to the reference device. The time point of measurement influences the output value. The heating of radiometers was proposed as a possible explanation for the inaccuracy.

Key words: *Dental curing lights; Radiometer; LED curing units; QTH curing lights*

Introduction

A high degree of polymerization of composite materials is necessary to ensure optimal mechanical properties: hardness, strength[1], wear resistance[2] and biocompatibility of materials, since residual monomers can cause allergic reactions[3,4], cytotoxic and genotoxic effects[5]. The extent of polymerization of composite materials depends on several factors. Among the factors influenced by the curing unit (CU), its light intensity, wavelength and appropriate duration of illumination are most important. Although the composite experienced great success in clinical practice, the awareness of the necessity of regular control of the polymerization units is still inadequate.

Polymerization units, especially quartz-tungsten-halogen (QTH), are susceptible to gradual deterioration of their properties. According to Shortall *et al.*[6], deviations in the values of polymerization light intensity may be the result of lamp aging, voltage fluctuations, failure of filter function, or damage to optical duct. Several studies have determined insufficient light intensity in dental offices all over the world[7-9]. Two studies conducted in dental clinics in Zagreb in 1999 and 2011 identified improvement in the quality of polymerization devices[10, 11]. In 1999, 44% of tested devices did not fulfill the minimal intensity values needed for adequate polymerization[10], while in 2011 this percentage decreased to 34%[11]. Although the improvement is visible, more than one-third of curing devices are not functioning properly. Periodic monitoring of light output by using radiometers can detect their defects.

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Intensity control of curing light is performed by radiometers, which can be hand-held or integrated in the CU. Different radiometers by various manufacturers are in use, which have mostly the same working principle. Dental radiometers usually contain silicon or selenium photodiodes that convert light into electric current, then an analogue or digital meter displays the output from the curing light[12]. However, they differ in wavelength they detect, the power they can express, and diameter of the circular light sources they can measure. Also, they can be adjusted for the measurement of QTH or light emitting diode (LED) devices by using filters for specific wavelengths. Even though radiometers are widely recommended for regular check-ups, several studies have established that they are unreliable[6,12-14]. Suggested reasons for their inaccuracy include variability of their original calibration, degradation over time[12] and inconsistency of the light tip diameter of the CU and the aperture of the sensor at the radiometer[15].

Recently, a representative of a new generation of dental radiometers, Bluephase meter (BM, Ivoclar Vivadent, Schaan, Liechtenstein) has been introduced to the market. It can measure various light guide tip sizes of 7-13 mm, and the wavelength range enables it to measure also the third generation of LED units, besides the other QTH or LED devices. On the other hand, Cure Rite (CR, Detsply Caulk, Mills, USA) is used primarily for measurement of the light intensity of QTH units. However, unlike BM, which shows only the results greater than 300 mW/cm^2, CR is able to determine lower values.

For accurate determination of the light intensity, the integrating sphere (Ulbricht) as an accurate physical instrument can be used. It is an optical device that has multiple purposes and is used to determine the absolute light intensity. The hollow sphere has two or more small apertures for inducting light or photo detector. It contains compartments that prevent direct illumination of the detector from the light source[16].

An excellent, recently published study has determined the large intra- and inter-brand variability of dental radiometers. More than ±20% variablity was recorded between the tested radiometers and the laboratory-grade power meter, but also a high difference in readings of the radiometers from different manufacturers, as well as a significant variation between the radiometer samples of the same brand[12]. However, among tested radiometers, all three examples of BM and one CR radiometer were bioequivalent to the gold standard. To the best of our knowledge, there are no studies that examined differences in the readings of dental radiometers according to the time point when the measurement was performed and the type of curing unit.

In this study, an integrating sphere was used as a gold standard that provides reliable measurements of irradiance. These values were compared with the readings of two hand-held radiometers. Similar studies that tested the effectiveness of dental radiometers by comparing their values with laboratory grade instruments are scarce[12,15,17]. Most of the studies compared several different kinds of light meters to each other[13,14,18], and correlated data to the degree of conversion of experimental composite measured by Fourier transform infrared spectroscopy[19] or to the depth of cure of commercial composite materials[20].

The aim of this study was to establish the effect of time on the measurement accuracy of the light intensity of LED and QTH photopolymerization devices using two generations of dental radiometers with reference to the laboratory-grade instrument. Null hypothesis was that there were no differences between the values obtained by the tested radiometers and integrating sphere for each type of the curing unit.

Materials and Methods

The study included 24 polymerization units, 16 QTH and 8 LED, whose light intensity was measured using three different devices. The two hand-held radiometers were from different manufacturers: Bluephase meter (BM) and Cure Rite (CR). Technical data are provided in Table 1. The reference device was an integrating sphere, Ulbricht's sphere (IS, Gigahertz Optik GmbH, Puchheim, Germany).

One examiner performed a total of 576 measurements. For each CU, the light intensity was measured for high polymerization mode, at the start of illumination, and 10 and 40 seconds after the start of illumination. Three measurements were made for each of the aforementioned variables. The procedure was identical for both radiometers and the IS, except for BM, which was not able to measure the values at 40

Table 1. Specifications of the handheld radiometers, as provided by the manufacturers

	Cure Rite (CR)	Bluephase meter (BM)
Manufacturer	Dentsply Caulk, Milford, USA	Ivoclar Vivadent, Schaan, Liechtenstein
Wavelength range	400-525 nm	380-520 nm
Light intensity range	0-1999 mW/cm^2	300-2500 mW/cm^2
Aperture size	6.5 mm	7-13 mm
Curing units	QTH	QTH and LED

QTH = quartz tungsten halogen; LED = light emitting diode

seconds. If CU had more programs, the measurement was conducted for a maximum continuous intensity.

During measurement, the light curing tip of polymerization device was pressed flush on the radiometer sensor and the determined values were expressed in mW/cm^2 (Fig. 1).

When measuring values of the IS, it was necessary to calibrate and adjust the measurement for halogen or LED devices. Then the tube diameter of polymerization unit was defined for adapting the extension that provided only the inflow of the CU light preventing light income from surrounding sources, which could lead to inaccurate results (Fig. 2). Values attained by the IS were expressed in mW and were recalculated into mW/cm^2 using surface specified with effective diameter, which is determined using a millimeter scale.

Shapiro-Wilk test was used to test the distribution of data. Data were statistically analyzed using Friedman's test and Wilcoxon signed-rank test ($p<0.05$).

Fig. 1. Reading of light intensity by Bluephase meter.

Results

The results obtained by the Shapiro-Wilk test indicated that the distribution of variables was not normal. Besides, the sample of LED units was small, so the Friedman and Wilcoxon rank sum tests were used. For comparison of the groups of variables, significant p-values of original samples were corrected by Bonferroni correction. Statistically significant differences in the distribution of mean values measured with an IS between the QTH and LED devices were detected in almost all intervals. Distribution of the

Fig. 2. Integrating sphere.

Table 2. Results of statistical analysis of group pairs for LED units performed by Wilcoxon signed-rank test

Variable	Test statistics (S)	p-value	Bonferroni p-value
BM start-IS start	18.0	p=0.0078	**p=0.0234**
BM 10-IS 10	18.0	p=0.0078	**p=0.0234**
CR start-IS start	6.0	p=0.4609	
CR 10-IS 10	18.0	p=0.0078	**p=0.0234**
CR 40-IS 40	18.0	**p=0.0078**	
BM start-CR start	0.0	p=1.0000	
BM 10-CR 10	-16.0	p=0.0234	p=0.0702

BM = Bluephase meter; CR = Cure Rite; IS = integrating sphere

mean values of LED devices for IS measurements had higher values than the distribution of the mean values of QTH devices (shifted more to the right).

Figure 3 shows descriptive statistical analysis of light intensity of LED units. As shown in Table 2, distributions of the measured values for LED units were significantly different between all group pairs, except for the initial measurements of CR and IS and the measurements at 10 seconds for BM and CR ($p<0.05$).

Figure 4 shows descriptive statistical analysis of the light intensity of QTH units. As shown in Table 3, distributions of the measured values for QTH units were significantly different between all group pairs, except for the initial measurements of CR and IS and the measurements at 10 seconds for BM and CR ($p<0.05$).

Analysis of CR and IS for both LED and QTH devices yielded significant differences in the distribution of recorded values at 10 and 40 seconds, where the values generally observed by CR were higher in both instances. The most accurate reading was at the start of measurement, with no statistically significant difference between CR and IS.

BM showed significantly higher values compared to IS at the beginning and after 10 seconds. However, there was no statistically significant difference between BM and CR at the measurements taken 10 seconds after the start of illumination.

Discussion

Study results indicated that the hand-held radiometers tested were not able to accurately measure the irradiance of LED and QTH units. The great influence of the light source type (LED or QTH) and the time point at which the measurement was taken (at the beginning, after 10 and 40 seconds of the polymerization cycle) were determined.

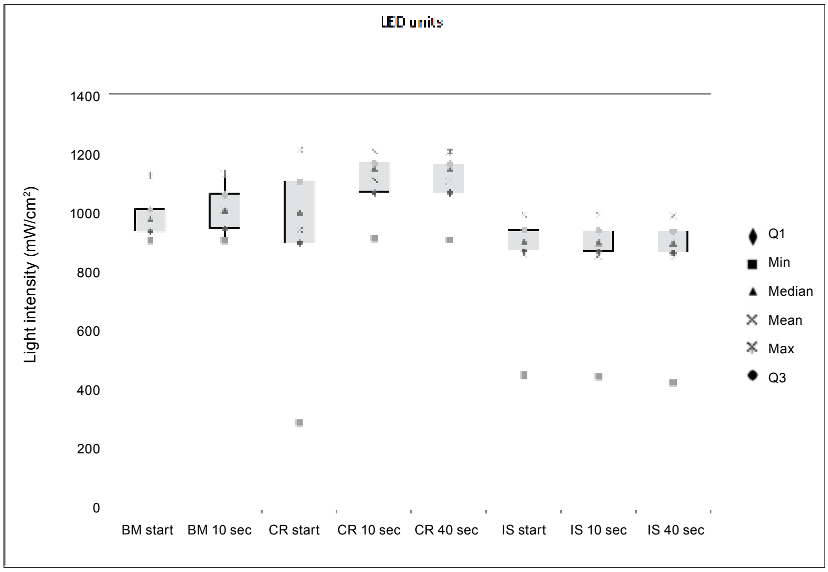
It is well established that dental radiometers do not give precise absolute values like laboratory instruments[12,15]. However, these more precise instruments

Table 3. Results of statistical analysis of group pairs for QTH units performed by Wilcoxon signed-rank test

Variable	Test statistics (S)	p-value	Bonferroni p-value
BM start-IS start	50.0	p=0.0076	**p=0.0228**
BM 10-IS 10	63.0	p=0.0003	**p=0.0009**
CR start-IS start	-13.0	p=0.5282	
CR 10-IS 10	60.0	p=0.0008	**p=0.0024**
CR 40-IS 40	61.0	**p=0.0006**	
BM start-CR start	64.0	p=0.0002	**p=0.0006**
BM 10-CR 10	32.5	p=0.0419	p=0.1257

BM = Bluephase meter; CR = Cure Rite; IS = integrating sphere

Fig. 3. Box plot diagram of measured light intensity values for LED units.



are often large and impractical for use in dental offices. On the other hand, it has been repeatedly emphasized that radiometer can provide relative information on the decrease in light intensity of a CU[13-15]. Dental radiometers are important not only for dental practitioners, but also for the scientists in the area of dental materials. Light intensity of the CU applied in scientific experiments may significantly influence the degree of conversion, hardness and strength of the tested light-cured materials[21-24], but it can also influence the interpretation of the results and their comparison with other studies.

The origin of inaccuracy of dental radiometers has not been completely understood. It has been established that the congruence of the tip of the light output of CU and the aperture of the radiometer are very important[6,15]. The inhomogeneous light distribution in the light output of CUs has been determined[17,25], the highest intensity being mostly positioned in the center of the light guide. Therefore, when such a larger light tip is positioned at the smaller radiometer aperture, higher irradiance readings can be expected. Contrary, smaller light output on a larger radiometer aperture will mislead to lower values. In the present study, the aperture size was selected according to the light tip diameter for measurements with IS, while the diameter of the CR radiometer is fixed to 6.5 mm. This could explain the higher results obtained by CR in comparison to IS. The diameter of the circular light source that BM radiometer can measure is in the range of 7-13 mm. Nevertheless, in the present study, the BM values were highest, which might be due to the factory calibration of the device. However, it is important to emphasize that both radiometers tested did not differ in the intensity readings after 10 seconds.

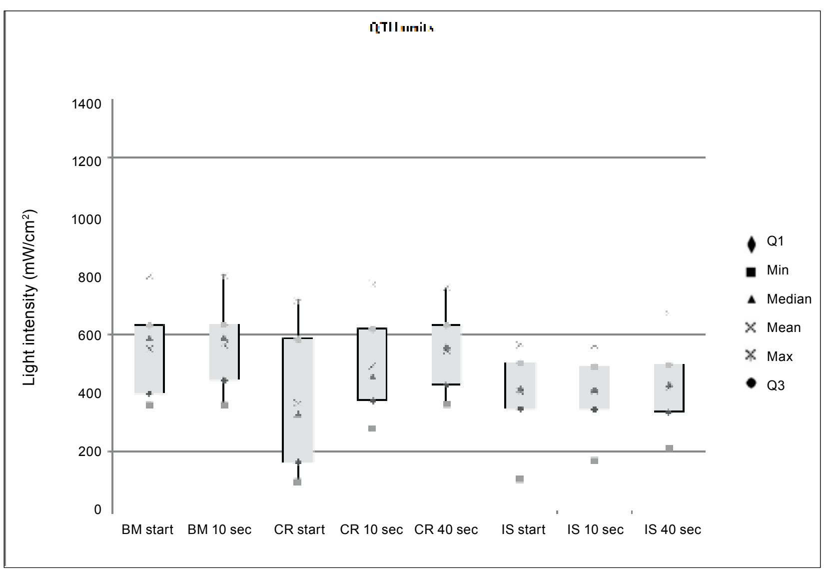


Fig. 4. Box plot diagram of measured light intensity values for QTH units.

The manufacturers advertise certain radiometers as LED or QTH oriented. However, none of the previous studies was able to distinguish radiometers that are more accurate for LED or QTH CUs[12,15]. The results of the present study indicated that BM consistently showed higher values than IS for both LED and QTH units. Contrary, CR showed an interesting phenomenon. A constant rise in the intensity values for both types of CUs was observed. This is in contrast to the findings of previous studies, which even found a small decrease after 60 seconds of illumination[26]. This effect was often explained by difference in voltage[27-29] and the time needed for heating of the device[17]. Since IS did not demonstrate such differences in light intensity of either LED or QTH devices, a different theory can be proposed.

As stated in the Introduction section, the light intensity of a CU is detected by a photodiode in the radiometer. Photodiode converts the incident light into electric current. Silicon photodiodes are semiconductor devices used for the detection of ultraviolet, visible and near infrared spectral regions[30]. Sometimes, they should be used with appropriate filters or optics. Because of their small size, high speed and good spectral response, they have a variety of applications. Noise from the outside, like heat and other energy sources, plays an important role in the efficiency of a photodiode. This is calculated into Johnson noise. The effect of Johnson noise can modify the voltage output of a photodiode by canceling out light waves[31]. Increase in the operating temperature of a photodiode device results in two distinct changes in operating characteristics. The first change is a shift in the quantum efficiency due to changes in the radiation absorption of the device. Quantum efficiency values shift lower in the ultraviolet region and higher in the infrared region. The second change is caused by exponential increases in the thermally excited electron-hole pairs resulting in increasing dark current. This leakage doubles for each 8 to 10 °C temperature increase[32,33].

Temperature increase of a photodiode inside of a radiometer might be responsible for the gradually higher light intensity readings. It is well documented that the light generation in QTH devices leads to the formation of excessive infrared energy[34,35]. The first generation of LED devices showed lower heating than QTH and plasma CUs[36,37], but thermal measurements of second and third generations demonstrate similar values to QTH devices of analogous intensities and higher values than the first generation LEDs[38,39]. This is a consequence of the higher power of LEDs used in the second and third generation devices. It was also demonstrated that temperature rise highly correlated with power density of a CU[34]. Temperature increase recorded at the light tip varies from 11 °C to 25°C[38,39], and it rises with the number of consecutive applications[40]. The insulating effect of dentine seems to prevent the formation of such high temperatures in the pulp[41], but in the present study, the direct contact of the light output to the radiometer might have a deleterious influence on the accuracy of its readings.

The above mentioned could be a feasible explanation for the results obtained. The constant rise in the intensity found in CR is in line with temperature rise at the contact point between the light tip of the CU and the radiometer (unpublished data from a pilot study). The heating of a photodiode within the radiometer as a consequence of the close contact with the CU during the measurement might be the reason for its inaccuracy. Therefore, the influence of time on the reliability of dental radiometers is actually related to the heating of the device through the close contact with CUs. Although the IS also has a photodiode as a detector of the irradiance, its much larger distance from the light source can minimize this thermal effect.

A disadvantage of BM was that it was not able to show the values at 40 seconds because it automatically switched off at 20 seconds. Additional 10 seconds are needed to reactivate it, during which the photodiode could cool off, so these values were not recorded. Also, the results were affected by the BM inability of recording polymerization light intensity values lower than 300 mW/cm^2. This fact is not important for clinical use, but for a scientific study, it was an aggravating circumstance because it was impossible to compare the results with the CR radiometer. This was the reason for discarding another 16 units from the original sample.

Within the limitations of the present study, it was determined that the radiometers tested were not accurate as a laboratory grade instrument. The time point of the measurement was established as an important factor influencing the output value, and it differs for LED and QTH CUs. The proposed explanation for the inaccuracy was found to be the heating of the radiometers. Therefore, the use of radiometers is not encouraged for scientific studies, but they are useful assistance in clinical work for daily monitoring of curing devices. Although they cannot display the values of light intensity with full accuracy, they can provide an insight into changes in the work of polymerization units. Clinicians are advised to always use the same time point for regular check-ups of their curing units.

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Sažetak

MJERNA TOČNOST STOMATOLOŠKIH RADIOMETARA OVISNO O VREMENU MJERENJA

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Neodgovarajući intenzitet svjetlosti polimerizacijskih uređaja može ugroziti kvalitetu i dugotrajnost stomatoloških kompozitnih restoracija. Kako bi se očuvala optimalna snaga polimerizacijskih uređaja neophodna je redovita kontrola. Svrha ovoga ispitivanja bila je usporediti dva radiometra u točnosti mjerenja intenziteta svjetlosti fotopolimerizacijskih uređaja uzimajući u obzir vrijeme mjerenja. Mjerenja intenziteta svjetlosti 16 halogenih i 8 LED polimerizacijskih lampa provedena su pomoću tri uređaja na početku iluminacije, te nakon 10 i 40 sekunda. Korištena su dva ručna radiometra: Bluephase meter (BM) i Cure Rite (CR), dok je integrirajuća sfera (IS) predstavljala referentni uređaj. Podaci su statistički analizirani pomoću Friedmanova testa i Wilcoxonova *signed-rank* testa ($p<0.05$). Vrijednosti izmjerene pomoću BM na početku i nakon 10 sekunda bile su značajno više od onih izmjerenih pomoću IS, dok je CR pokazao više vrijednosti nakon 10 i 40 sekunda. Oba komercijalno dostupna radiometra pokazala su tendenciju prikazivanja viših vrijednosti intenziteta svjetlosti LED i halogenih polimerizacijskih uređaja u usporedbi s referentnim uređajem. Vrijeme mjerenja ima utjecaja na očitanje intenziteta svjetlosti. Zagrijavanje radiometara je predloženo kao moguće objašnjenje njihove nepreciznosti.

Ključne riječi: *Stomatološki polimerizacijski uređaji; Radiometar; LED polimerizacijski uređaji; QTH polimerizacijski uređaji*