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Output intensity of LED light curing units over a 4-year period of clinical use

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Objectives: The objective of this study was to compare the surface hardness of a self-cured injection-molding denture base material, which its curing process was modified from that recommended by the manufacturer, when stored in water at 7 days and 30 days.

Materials and Methods: Ten rectangular specimens (10 mm x 64 mm x 2.5 mm) in three groups of injection-molding denture base materials were prepared from separate mix. The first group contained SR Ivocap® High Impact heat-cured specimens which were polymerized in water at 100°C according to the manufacturer's instruction (Ivocap wet curing). The second group was IvoBase® Hybrid self-cured injection-molding specimens which were polymerized via the injection machine at 40°C up to120°C (IvoBase dry curing). The third group was IvoBase® Hybrid specimens which were mixed according to the manufacturer's instruction but the processing method was the same as Ivocap wet curing. The Vickers hardness of the specimens were measured at 7 and 30 days of water storage. Split-plot ANOVA was used to analyze the data at α=0.05.

Results: The surface hardness of IvoBase® Hybrid when polymerized according to the manufacturer's instruction and when polymerized with a modified method were not significantly different at both 7 days and 30 days storage in water. The surface hardness of IvoBase® Hybrid was significantly higher than that of SR Ivocap® High Impact. The hardness of IvoBase® Hybrid significantly increased when they were stored in water for a longer time from 7 days to 30 days. The surface hardness of SR Ivocap® High Impact significantly decreased with water storage from 7 days to 30 days.

Conclusions: The modified curing technique of IvoBase® Hybrid did not alter the surface hardness characteristics of the material. Time of storage in water had an effect on the material's hardness differently. The hardness of the self-cured material increased with increasing storage time from 7 days to 30 days, whereas the hardness of the heat-cured material decreased.

Keywords: acrylic resin, denture base material, injection molded acrylic resin, surface hardness

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Introduction

Currently, the extensive use of resin composite is increasing because of the demand for esthetic restorations in restorative dentistry. [1] Resin composite must be activated for optimal polymerization in order to obtain the proper physical and mechanical properties.

In resin composite, camphorquinone is generally used as an initiator system to create free radicals and initiate the polymerization reaction. [2] An appropriate light intensity and exposure time with the maximum absorption wavelength range of the initiator system are the most important factors for polymerizing resin composite. Camphorquinone is the most commonly used initiator. Camphorquinone absorbs light in

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the wavelength range of approximately 390 to 510 nm. [3] The International Organization for Standardization defines the light intensity of curing units as the ISO 4049 standard, which recommends an acceptable intensity for clinical use of 300 mW/cm^2 with a wavelength range of 400-515 nm. [4]

If an inappropriate intensity of curing light is used, insufficient polymerization of the resin composite may occur. [5] This has been shown to have the potential to cause a number of adverse consequences, including the following: reduced hardness and wear resistance [6-10], weaker adhesion to the tooth [11-12], increased marginal leakage from dissolution of composite resin at the gingival margin [13], increased bacterial colonization onto the composite [13], reduced color stability [14], higher release of elutable substances and increased cytotoxicity [15-16], risk for postoperative sensitivities, secondary caries, and fracture of restorations [6-7,17].

Important factors of light curing units affecting the intensity of the light output are: inappropriate performance of the lamp and filter, breakage and pollution of the curing tip, blurring of the bulb, failure of electrical components, and defect in the light transmitting fibers. [18-19] In these curing units, if maintenance is not carried out routinely, there will eventually be some problems with the lamp, fan, or power supply. [20] Thus, the output light of the curing unit decreases as the device is increasingly used. Therefore, a digital radiometer is needed to measure the intensity of the curing light to determine when the device needs to be repaired or replaced. [21]

Currently, there are various light sources available for the polymerization of resin composite, such as quartz-tungsten-halogen, plasma arc, metal halide, argon laser and light-emitting diodes (LED). [18] With an LED curing unit, instead of the hot strands that are used in halogen lamps, plasma arc, or a metal halide curing unit, semiconductors are used to produce blue visible light at wavelengths between 440-480 nm. These light sources have a very long shelf life of approximately 1,000 hours and very low error rates. [19]

The LED curing unit can be divided into two category of mono-wave curing units that typically have narrow spectral emission (430-480 nm) and dual-wave curing units with broad spectral emission ranging between 385 and 515 nm. The dual-wave curing units might be more suitable for initiation all initiators used in light-cured dental materials. [22,23]

Many reports used the intensity at 300 mW/cm^2 as the minimum acceptable irradiance of curing units for clinical use [4,24-25]. The 79.2 percent of LED curing units delivered at least 300 mW/cm^2 with 1-3 years period of clinical use has been reported and used as the shelf life of the LED curing unit. [25] Currently, according to the ISO 10650-2:2018 standard, the acceptable irradiance of measured value of current LED curing units should be no less than 9% of minimal intensity given by the manufacturer has been proposed.

The aims of the present study were: 1) to measure and compare the light intensity of different LED light curing units including mono-wave curing unit and dual-wave curing in regard to their clinical use over 4 years, 2) to determine the relationship between the clinical age of these curing units and their light intensity, and 3) to identify the reasons for and the frequency of repairs to these curing units.

Materials and Methods

The maintenance data of 243 LED curing units from 8 clinics (The HRH Princess Mahachakri Sirindhorn's Mobile Dental Service Center, Special Clinic, Pediatric Dental Clinic, Main Clinic, Orthodontic Clinic, Operative Dentistry Clinic, Prosthodontic Clinic and Advanced General Dentistry Clinic) were analyzed. These 8 clinics were selected from 18 clinics of the Dental Hospital, Faculty of Dentistry, Mahidol University because of the integrity of collected data.

Four LED curing units (Bluephase G2, Bluephase Style, Demiplus and Elipar S10) were used in 8 clinics. The data from these curing units were analyzed in the present study. The information of these curing units is demonstrated in Table 1. Regarding to the ISO 10650-2: 2018 standard, the irradiance minimum for each curing unit was calculated by the following equation: the irradiance minimum = the intensity of the minimum intensity given by the manufacturer – 9% of the intensity of the minimum intensity given by the manufacturer. The irradiance minimum is demonstrated in Table 1.

The spectral emission and spectral radiant power (Watts/nm) from the light curing units of each manufacturer were determined using calibrated spectrometer-based systems (Everfine CAS-200 Compact Array Spectrometry, Everfine Photo-E-Info Co.Ltd., Hangzhou, China). To measure the light intensity, a digital radiometer (Bluephase Meter, Ivoclar Vivadent, Schaan, Liechtenstein) with a range of measurable wavelength of 380 to 515 nm and a range of measurable output intensity of 300-2,500 mW/cm^2 was used. Then, three measurements of the light intensity were recorded for each light curing unit by one investigator, and the average was reported as the final measurement. For measurement with the radiometer, the tip of light guide was place onto the sensor with position the light probe exactly on the line sensor by means of the centering gauge. The switch of the curing unit was turned on. The intensity was recorded. The collected data at the day of checking equipment before clinical use (0 year), the data of 4-year clinical use (4 years), and the data of 8-year clinical use (8 years) were used for analysis of periods of clinical use. A light intensity of less than 300 mW/cm^2 was considered clinically unacceptable [4,25], and these devices were further investigated with an analogue radiometer (LED Radiometer, SDS Kerr, Middleton, WI, USA) with a range of measurable wavelength of 400 to 500 nm and a range of measurable output intensity of <2,000 mW/cm^2. Thus, the intensity of higher than the irradiance minimum of each curing unit was considered acceptable irradiance according to the ISO 10650-2: 2018 standard.

In addition, data on the age of unit, the frequency of use per week, the clinical age, and the reasons for repair were obtained from the database of the Physical and Environmental Sections, Faculty of Dentistry, Mahidol University.

Table 1 LED curing units used in this study.

Product	Type	Wavelength	Intensity	Irradiance minimum	Curing tip
Bluephase G2 Ivoclar Vivadent Schaan, Liechtenstein	Gun type	Dual wave 385-515 nm	Low 650 mW/cm^2 High 1,200 mW/cm^2	Low 591.50 mW/cm^2 High 1,092.00 mW/cm^2	Straight 10 mm
Bluephase Style Ivoclar Vivadent Schaan, Liechtenstein	Pen type	Dual wave 385-515 nm	High ≤ 1,000 mW/cm^2	High 910.00 mW/cm^2	Straight 10 mm
Demi Plus SDS Kerr Middletin, WI, USA	Pen type	Mono wave 450-470 nm	High 1,100-1,330 mW/cm^2	High 1,001.00 mW/cm^2	Straight Turbo 11/7 mm
Elipar S10 3M ESPE St. Paul, MN, USA	Pen type	Mono wave 430-480 nm	High 1,200 mW/cm^2	High 1,092.00 mW/cm^2	Straight 10 mm

Data are from the product manufacturers.

The collected data were pooled and analyzed using SPSS version 18 (SPSS Inc, Chicago, USA). The mean and standard deviations of the light intensity of the light curing units were used for statistical analysis with an α level of < 0.05. The data from the damaged curing units that required repairing were not included for statistical analysis. The two-way ANOVA was used to analyze the effect of 2 major factors (the different curing units and the age of unit) on the output light intensity, and Tukey's HSD test was used to define the difference of mean between the groups.

The clinical age of the device was calculated using the following equation: clinical age = the age of unit (in terms of years) x 52 (number of weeks in a year) x typical usage time per week (in terms of amount of time) x curing times per typical usage time (number of hours used per typical usage time). An average of 5 minutes for usage time per time of typical usage from clinical observation was used for the calculations in this study. The Pearson correlation coefficient (r) was used to determine the correlation between the clinical age and the output intensity of each curing unit. Furthermore, the regression was defined to model the relationship between clinical age and output light intensity through fitting a linear equation for each curing unit.

In addition, a descriptive statistical analysis was used to explain the frequency of device repair and the reason for repair of the curing units.

Results

Information was obtained from 243 LED curing units, including 32 Elipar S10 units (4 years for age of unit, 6 times/week frequency of use, 104.00 hour of clinical age) from the HRH Princess Mahachakri Sirindhorn's Mobile Dental Service Center, 49 Bluephase G2 units (8 years for age of unit, 122 times/week frequency of use, 4,229.22 hour of clinical age) from the Special Clinic, 15 Bluephase G2 units and 3 Demi Plus units (8 years for age of unit, 11 times/week frequency of use, 381.33 hour of clinical age) from the Pediatric Dental Clinic, 34 Bluephase G2 units and 15 Bluephase Style units (8 years for age of unit, 22 times/week frequency of use, 762.67 hour of clinical age) from the Main Clinic, 40 Bluephase G2 units (8 years for age of unit, 6 times/week frequency of use, 208.00 hour of clinical age) from the Orthodontic Clinic, 15 Bluephase G2 units and 1 Bluephase Style unit (8 years for age of unit, 14 times/week frequency of use, 485.33 hour of clinical age) from the Operative Dentistry Clinic, 21 Bluephase G2 units and 4 Demi Plus units (8 years for age of unit, 22 times/week frequency of use, 762.67 hour of clinical age from the Prosthodontic Clinic, and 14 Bluephase G2 units (8 years for age of unit, 39 times/week frequency of use, 1,352.00 hour of clinical age) from the Advanced General Dentistry Clinic. The data are shown in Figure 1. A high frequency of use was found with the Special Clinic, with usage of 122 times per week or 2114.67 hours/4 years of clinical age or 4229.33 hours/8 years of clinical age. A low frequency of use was found with the HRH Princess Mahachakri Sirindhorn's Mobile Dental Service Center, with usage of 6 times per week or 104 hours/4 years of clinical age.

Of the 243 LED light curing units, 188 (77.37%) were Bluephase G2 units, 16 (6.58%) were Bluephase Style units, 7 (2.88%) and 32 were (13.17%) Elipar S10 units; this information is summarized in Figure 2. Only the Bluephase G2 can irradiate with 2 ranges of intensity: 650 mW/cm^2 in LOW mode and 1,200 mW/cm^2 in HIGH mode. Other LED curing units can irradiate only with a high intensity greater than 1,000 mW/cm^2 (Table 1).

The spectral emission and spectral radiant power (Watts/nm) from the light curing units of each manufacturer determined using calibrated spectrometer-based systems are demonstrated in Figure 3. Bluephase G2 and Bluephase Style showed two-peak of spectral emission. Demi Plus and Elipar S10 showed single peak of spectral emission.

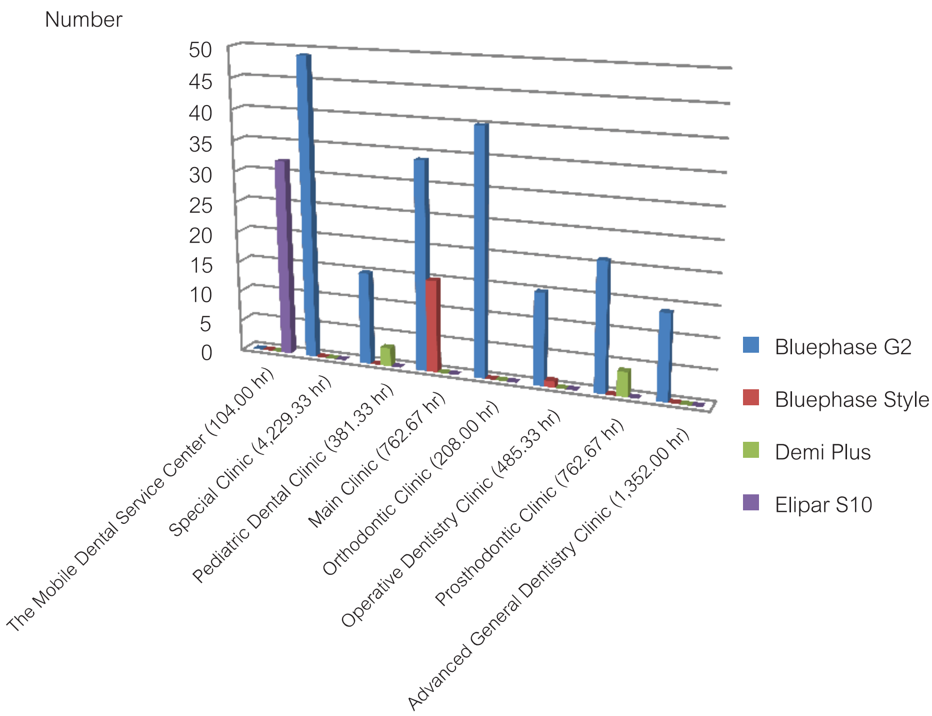

Figure 1 Information of the two hundred and forty-three LED curing units used in this study. The numbers in parenthesis are the clinical age (hr: hour).

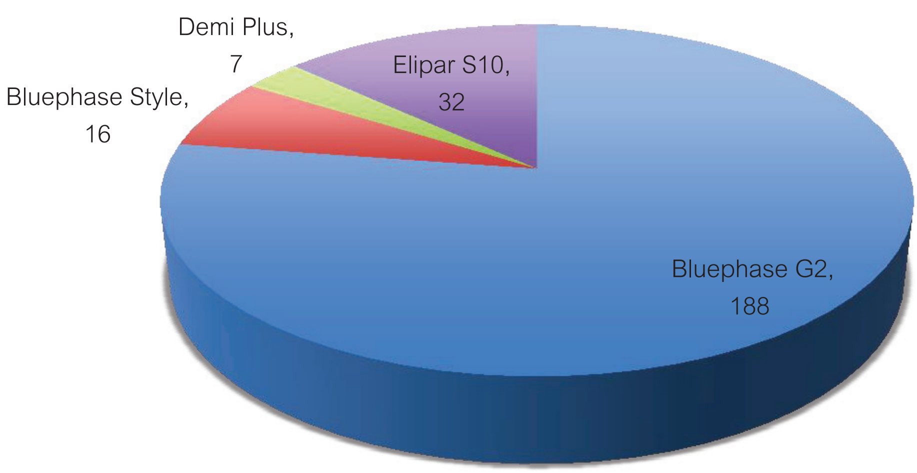

Figure 2 Numbers of the 4 different LED curing units used in this study.

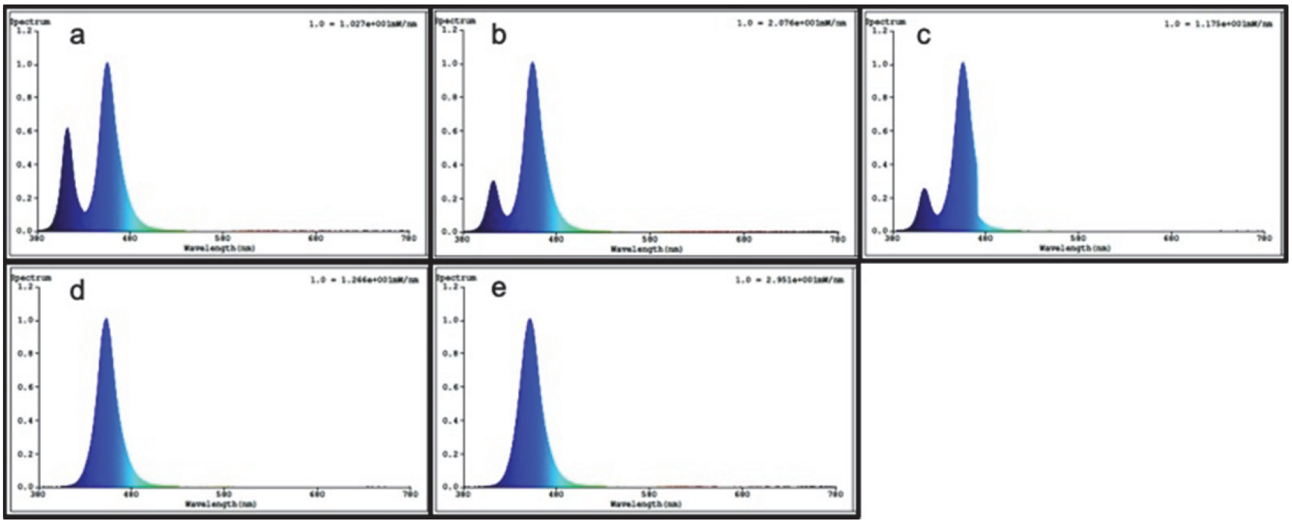

Figure 3 Spectral emission of the different LED curing units used in this study. (a: Bluephase G2 High Intensity, b: Bluephase G2 Low Intensity, c: Bluephase Style, d: Demi Plus, e: Elipar S10).

The desirable light intensity of LOW mode from the Bluephase G2 is demonstrated in Table 2. There was no significant difference between the light intensity of the curing unit at 0 year and 4 years of the clinical use. A significant reduction of the light intensity was found at 8 years of clinical use ($p < 0.01$).

The optimal intensity of curing light from the four LED curing units is demonstrated in Table 3. The effects of period of clinical use and the differences in curing units to light intensity were observed, with a significant level of $p<0.01$. The light intensity of almost all curing units at 0 year was not significantly different, except for the Bluephase Style. At 4 years, the intensity of the Bluephase G2 was significantly higher than that of other curing units. At 8 years, there were no significant differences in the light intensities between the Bluephase G2 and the Demi Plus, which were significantly higher than the intensity of the Bluephase Style. Additionally, the intensity of the Elipar S10 at 4 years of age was less than that at 0 years. The intensity of the Bluephase G2 and the Bluephase Style at 8 years reduced significantly when compared with the intensity at 0 year and 4 years. There was no change in intensity among the different clinical ages for the Demi Plus.

The average output intensity from all tested curing units were over than the irradiance minimum for both low and high intensity mode.

The correlation and regression models between clinical age (T: hours) and output intensity (I: mW/cm^2) of different curing units are demonstrated in Tables 4 and Figure 4. The Pearson correlation revealed a negative relationship between clinical age and output intensity for the Bluephase G2, Bluephase Style and Elipar S10, at a significance level of $p<0.01$. However, the correlation between the clinical age and output intensity for the Demi Plus had a significant level of $p=0.246$.

Table 2 The means and standard deviations of the light intensity (mW/cm^2) of the Bluephase G2 in low intensity mode.

Periods of clinical use	0 year	4 years	8 years
Bluephase G2	660.90 ± 27.47^a	658.35 ± 21.24^a	593.67 ± 92.86^b

The data with the same superscript demonstrated no statistically significant difference.

Table 3 Means and standard deviations of the high intensity (mW/cm^2) of curing light from the 4 LED curing units.

Periods of clinical use	0 year	4 years	8 years
Bluephase G2	1219.63±54.33^{a,A}	1221.68±47.05^{a,A}	1102.07±115.01^{b,A}
Bluephase Style	1120.87±58.02^{a,B}	1099.31±50.13^{a,C}	987.50±107.42^{b,B}
Demi Plus	1190.00±62.72^{a,A}	1170.71±59.75^{a,B}	1174.28±340.58^{a,A}
Elipar S10	1182.50±58.86^{a,A}	1115.31±52.67^{b,C}	n.a.

Data with the same superscripts demonstrated no statistically significant difference. The small letters demonstrate statistical analysis among rows. The capital letters demonstrate statistical analysis among columns.

Table 4 The correlation between the clinical age and output light intensity of different curing units.

Curing unit	Intensity	r	r^2	p-value
Bluephase G2	Low	0.717	0.514	p<0.01
	High	0.643	0.413	p<0.01
Bluephase Style	High	0.530	0.218	p<0.01
Demi Plus	High	0.265	0.070	P=0.246
Elipar S10	High	0.521	0.272	p<0.01

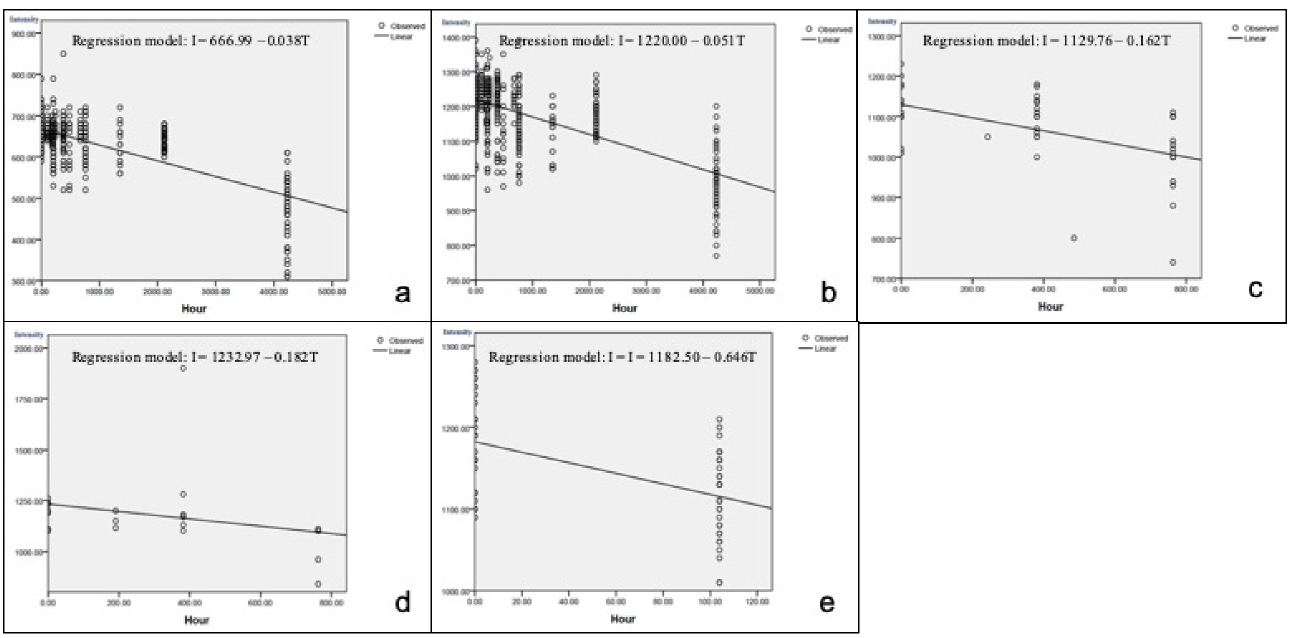

Figure 4 The regression models between clinical age and output intensity of different curing units; I: light intensity (mW/cm^2), T: clinical age (hours). (a: Bluephase G2 with low intensity mode, b: Bluephase G2 with high intensity mode, c: Bluephase Style, d: Demi Plus, e: Elipar S10).

Table 5 The frequency of device repair and the reason for repair

Curing units	Broken part	Frequency	Percentage
Bluephase G2	Battery	10	4.12
	O-rings	9	3.70
	Light probe	3	1.23
	Display	3	1.23
	Charging base	2	0.82
Bluephase Style	Light probe	1	0.41
	Reflector	2	0.82

The frequency of device repairs and the reason for the repair of each device is shown in Table 5. According to Table 5, most of the problems with the curing units occurred after 7 years of clinical use. The most common reason for repair after 7 years of use was damage to the battery. The solution for this problem was replacement with a new battery. Another problem was the degradation of curing tip O-ring that caused instability of the light probe. The replacement with a new O-ring improved the stability of the light probe. Breakage of the reflector of the LED light source only occurred in two of the Bluephase Style units, which caused reduction of the light intensity down to less than 300 mW/cm^2 (200, 250 mW/cm^2). A replacement with a new reflector of LED light source for Bluephase Style units was necessary to restore the light intensity to the optimum intensity of about 1,100 mW/cm^2.

Discussion

For current resin-based materials, not only camphorquinone (CQ) but also other initiator systems such as diphenyl (2,4,6- trimethylbenzoyl)-phosphine oxide (TPO) or phenyl-propanedione (PPD) were incorporated into some materials. The CQ initiator absorbs light in the wavelength range of 390 to 510 nm, whereas the TPO and PPD absorb light in the wavelength range of 380 to 430 nm. [3, 20, 26] The ability of a curing light to cure all dental materials and photoinitiator systems depends on the spectral emission of the curing light. The mono-wave curing units that typically have narrow spectral emission (430-480 nm) might not be suitable to polymerize all restorative materials. The dual-wave curing units that have a spectral range between 385 and 515 nm might be more suitable for polymerizing all light-curing materials. [22, 23]

The minimum intensity recommended for curing a layer of composite resin is at least 400 mW/cm^2, and curing units with an intensity less than 300 mW/cm^2 should not be clinically used. [4,27] In the present study, none of the currently used curing units irradiated light with an intensity less than 300 mW/cm^2. Only curing units with a history of a broken reflector showed an intensity less than 300 mW/cm^2. Therefore, the light intensity of these broken units was returned to the optimum intensity of approximately 1,100 mW/cm^2 after replacement with a new reflector.

A minimum value of 1,000 mW/cm^2 may be considered to be the current ideal intensity. The use of high intensity curing light may allow for shorter exposure times or compensate for irradiation through tooth structures or ceramic restorations in indirect restorations. This may ensure that a high degree of conversion of resin-based materials is obtained. [28,29] With a high intensity, >1,000 mW/cm^2, the curing time of a layer of composite may be reduced to 10-20 sec. Therefore, the use of sufficient curing times even with high intensity LEDs to ensure adequate curing and minimization of the risk of monomer leaching should be major concern. [30] All curing units in this study showed an intensity greater than 1,000 mW/cm^2 for high intensity mode until 4 years of use. Some of the curing units showed an intensity less than 1,000 mW/cm^2 after 8 years of use, even though the average light intensity of all tested groups was higher than 1,000 mW/cm^2 for high intensity mode. Therefore, all curing units still had measured intensity over the requirement set by the ISO10650-2:2018 that were calculated and used as irradiance minimum.

A negative correlation between the clinical age and the output light intensity of curing units was observed in this study, which was in agreement with previous studies. [31-32] Therefore, differences of the Pearson correlation coefficient values (r) were observed. The Demi Plus showed the least value of r=0.265. The differences between the light curing units may have resulted in differences in the Pearson correlation coefficient values. However, negative relationship between clinical age and output intensity should be of more concern. The aging and frequency use of the device might be the potential factors contributing to the light intensity. In order to use this compromised curing-units, an increase in curing times greater than that of the manufacturer's recommendation may be recommended to maintain optimum polymerization of the materials. [27] Thus, the light intensity should be checked regularly as the output capacity of the curing light decreases with age. Radiometers are helpful tools to measure the intensity output. [33]

Furthermore, only two curing units required replacement of the reflector. The reason for the replacement was not due to degradation of the LED but instead due to accidental breakage of the reflector. This observation demonstrated the long shelf life of 4,229 hours of clinical age of the LEDs from Special Clinic. Other parts of the curing units, such as battery (4.12%) and O-ring (3.70%), showed degradation after 7 years of clinical use.

For the shelf life of investigated LED curing units, 100 percent of LED curing units irradiated at least 300 mW/cm^2 with over than 4 years period of clinical use that was higher than a previous report of 79.2 percent within 3 years period of clinical use. [25] Thus, the delivered intensity from all tested curing units were over than the irradiance minimal for both low and high intensity mode. This may be considered as acceptable irradiance.

To guarantee success of clinical outcomes, light intensity measurement and regular maintenance should be carried out to ensure the optimal efficiency of the LED curing units.

Conclusions

Within the limitation of this study, the optimal intensity of LED curing units demonstrated an average output intensity of >1,000 mW/cm^2 over a 4-year period of clinical use. The output intensity from all tested curing units for both low and high intensity mode were over than the irradiance minimum proposed by ISO 10650-2: 2018. Therefore, a decrease in the output intensity was related to an increase in clinical age.

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