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The Ability of Dental Practitioners to Light-Cure Simulated Restorations

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Clinical Relevance

Using a patient simulator, dental professionals were tested to determine their ability to light-polymerize simulated restorations in their dental practice. After receiving specific instructions and training using the simulator, their ability to deliver sufficient light to polymerize restorations was significantly and substantially improved.

SUMMARY

Objectives: To determine the ability of dental professionals to deliver a radiant exposure of at least six J/cm^2 in 10 seconds to simulated restorations.

Methods and Materials: The study initially examined 113 light-emitting-diode (LED) light polymerization units (LPUs) used in dental offices to determine if they could deliver at least 6 J/cm^2 radiant exposure (RE) in 10s. This assessment was completed by using a laboratory-grade light measuring device (checkMARC, BlueLight Analytics, Halifax, NS, Canada). The participating dental professionals whose LPUs could deliver 6 J/cm^2 then used their own LPU to light-cure simulated anterior and posterior restorations in the MARC Patient Simulator (BlueLight Analytics). They then received specific instructions and were retested using the same LPUs. Data were statistically analyzed with a series of one-way analysis of variance (ANOVA), two-way ANOVA, paired-samples *t*-tests, Fisher *post hoc* multiple comparison tests, and McNemar tests with a preset alpha of 0.05 (SPSS Inc).

Results: Ten (8.8%) LPUs could not deliver the required RE to the checkMARC in 10s and were eliminated from the study. For the anterior restoration, most dental practitioners (87.3%) could deliver at least 6 J/cm^2 before instructions. After receiving additional light-curing instructions, only two (1.9%) participants were unable to deliver 6 J/cm^2 to the anterior location. At the posterior location, only 55.3% (57) participants could deliver at least 6 J/cm^2 before the instructions. After receiving these instructions, an additional 32 participants delivered at least 6 J/cm^2. Overall, after receiving instructions on how to use the LPU correctly, the participants improved the amount

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of RE they delivered to anterior and posterior restorations by 22.5% and 30%, respectively.

Conclusion: This study revealed that at the baseline, 44.7% of participating dental professionals failed to deliver 6 J/cm^2 in 10s to the posterior simulated restoration when using their own LPU.

INTRODUCTION

Given the demand for natural-looking restorations and environmental concerns regarding mercury in amalgam restorations,[1,2] light-polymerized resin-based composites (RBC), have become the material of choice for many restorative procedures.[3] The clinical success of these light-activated materials depends on the combined abilities of the dentist and the light polymerization unit (LPU) to deliver adequate quantities and appropriate wavelengths of light to the RBC[4] so that it reaches its expected mechanical properties. Although RBC placement is a technique-sensitive procedure that requires attention to small details, the light-polymerization usually does not receive the same consideration as it should.[5,6]

It is well-known that insufficient polymerization has a detrimental impact on the mechanical properties and longevity of RBCs and, under polymerized resin with residual monomers, can pose health concerns as it leaches into the oral cavity.[7,8,9] The light-emitting diode (LED) LPU has become the most popular LPU for dental practice.[10,11,12] However, results from a recent study revealed that most dental practitioners are unaware of whether the LPUs in their offices can adequately polymerize their RBC restorations.[13]

Some dental practitioners use dental radiometers to evaluate their LPUs; however, most of these devices are inaccurate.[14,15,16] Even the best, the Bluephase Meter II (Ivoclar-Vivadent, Schaan, Liechtenstein),[17] only claims an accuracy of ±10%. In addition, dental radiometers measure the radiant exitance (mW/cm^2) at the surface of the light source and not what might be received by a restoration intra-orally. Also, unless they are recalibrated regularly, dental radiometers may produce inaccurate results as they age.[18]

Although the radiant exitant values measured by a spectroradiometer connected to an integrated sphere are considered to be the most accurate, the equipment is expensive and requires yearly recalibration. Also, since the radiant exitant values are measured with no distance between the light probe and the measuring device, this information is not particularly helpful to clinicians regarding how well they can deliver light to their RBC restorations.[19,20] Rarely is the distance between the light-tip and the resin in the mouth 0 mm. For instance, the distance in the molar region between the cusp tip and the bottom of the class II proximal box can exceed 8 mm, and this would significantly reduce the irradiance received by the RBC.[21-24]

Dental practitioners always strive to provide efficient and adequate polymerization of RBC restorations within a clinically acceptable time frame. Although anterior RBC restorations can be easily accessed and light-polymerized, access to posterior restorations poses a challenge. For example, correct light-tip positioning and alignment over the restoration can sometimes be challenging. When going further posterior to the upper first molar, proper positioning of the LPU tip over the restoration becomes even more challenging due to the obstructed view and the physical size of the LPU. Unless care is taken to overcome these obstacles, inadequate polymerization of the first RBC increment at the bottom of the class II proximal box can occur.[25,26]

Sufficient polymerization of RBCs depends on several key factors: the ability of the LPU to produce an adequate radiant exitance at the correct wavelengths, intrinsic properties of RBCs, and the technique used to deliver the light to the restorations.[27,28,29] However, the exact quantity of RE required to polymerize the RBC remains unanswered adequately. The *Phillips' Science of Dental Materials*[30] textbook recommends that, on average, 16 J/cm^2 should be delivered to a single 2-mm increment of conventional RBC material to achieve sufficient polymerization. However, this recommendation may not apply to all shades and opacities of RBCs or to bulk-fill materials,[31,32] and some studies[33-36] had reported that REs from 3 to 48 J/cm^2 are required depending on the specific RBC.

With the introduction of the MARC Patient Simulator (PS) (BlueLight Analytics, Halifax NS), it is now possible to accurately measure the RE received by simulated restorations made in a mannequin head. The MARC PS device incorporates a laboratory-grade ultraviolet-visible (UV-VIS) spectroradiometer (USB4000, Ocean Insight, Largo, FL) and two cosine-corrected sensors.[37] The sensors are 4 mm in diameter, which is the diameter of the ISO depth-of-cure mold[38] and similar to a medium-sized class I cavity. One anterior sensor is positioned between the maxillary central incisors, 1 mm below the facial surface (a simulated class III cavity), and a second sensor is located in the maxillary left second molar. It is placed at the base of a class I cavity preparation, 2 mm below the cavosurface margin and 4 mm below the cusp tip.[37]

Numerous studies have assessed light-polymerization techniques using the MARC PS.[39-47] However, these previous studies were conducted in academic settings, assessing dental students and dental professionals using preselected LPUs. The results revealed that the dental education that had been provided to the test subjects was inadequate to teach them how to deliver the maximum RE from the LPU. The results suggested that the MARC PS helped teach the use of the LPU.[44,46] The results of previous studies had shown that after receiving additional instructions on light curing that included the use of blue-light protective glasses and the recommendation to use a two-hand polymerization technique, the participants delivered significantly higher amounts of light to the simulated restorations. However, so far, no study has taken the MARC PS to the dental office and assessed the participating dental professionals using their own LPUs.

The focus of previous studies[13,48-55] was to measure the radiant exitance at the tip of the LPUs in dental practices and to compare the value with a specified study value. The majority of these studies used dental radiometers to test the LPUs, and they have shown that the light output from LPUs has increased in recent years. The LED-LPUs have become the most popular LPUs used in dental offices,[56,57] and the ISO 10650:2018 standard covers the features and use of LPUs.[58] However, the standard does not stipulate a minimum radiant exitant value, only a maximum value.[58] As well as the general increase in the radiant exitance values from LPUs, some studies have reported a trend to use monowave LED-LPUs rather than multiwave LPUs.[13,59-60]

Thus, this study evaluated the ability of dental professionals in private dental practices to deliver at least 6 J/cm^2 in 10s to the MARC PS–simulated restorations using their own LED-LPUs. The study addressed the following research hypotheses:

1. The participating dental professionals would be able to deliver RE of at least 6 J/cm^2 in 10s to simulated anterior and posterior restorations.
2. The average RE level delivered to simulated anterior and posterior restoration would increase significantly as a result of the operators receiving specific instructions on the proper light polymerization technique they should use.
3. The participants using multiwave or monowave LED-LPUs would deliver a similar RE to the MARC PS restorations.
4. The three professional groups examined (male dentists, female dentists, and dental assistants) would deliver similar RE values.

METHODS AND MATERIALS

After receiving approval from the University Research Ethics Board (#23060014), more than 350 prospective practices were identified and asked to participate. A total of 250 qualified dental practices expressed willingness to participate, and they were provided with information about the study and consent forms. However, some of those practices declined to participate, and eventually, only 113 dental practices participated in the study. The recruitment criteria included a general dental practice within the Metropolitan Area, which was divided into four quadrants (NE, NW, SE, and SW) with a similar number of practices recruited in each quadrant. All the offices were using LED-LPUs.

The study examined the ability of 113 LPUs to deliver at least 6 J/cm^2 RE in a 10s exposure at a distance of 0 mm from the light-tip. The initial assessment used checkMARC (BlueLight Analytics), a laboratory-grade spectroradiometer with a range of 0 to 10,000 mW/cm^2, which has a scientific-grade accuracy (an accuracy of +/- 5%).[61] The list of LED-LPUs tested is presented in Table 1. This assessment revealed that 10 LED-LPUs (8.8%) could not deliver 6 J/cm^2 and were eliminated from the next phase of the study. The ability of the remaining 103 LED-LPUs participants' polymerization technique to deliver the required RE was measured at the participating dental practices using a commercially available testing device (MARC PS). None of the participants in the study had prior experience with the MARC PS device (Figure 1). MARC software (MARC PS version 3.4) provided real-time RE data display and calculated the irradiance and the radiant exposure delivered within user-defined spectral ranges in a 10s exposure time.

Of the 103 LPUs tested, 39 were multiwave, and 64 were monowave LED-LPUs. Considering the wide range of manufacturers of the tested LED-LPUs and the previous studies' designs, this study required that at least a RE of 6 J/cm^2 would be delivered in 10s. Thus, the study design included three test groups of LPUs that could deliver: 6-7.99 J/cm$^{2;}$ 8-9.99 J/cm$^{2;}$ 10+ J/cm$^{2.}$

The study participants (n=103) were asked to use their LED-LPUs as they usually used the light to polymerize a restoration intra-orally for their patients. They were tested using the MARC PS and had the choice to use eye protection (handheld screens, protective glasses) or not to use eye protection. The participants were asked to simulate light-curing an anterior restoration by shining the LED-LPU onto the MARC PS anterior sensor (between upper central incisors) and performed a 10s test cycle that was repeated three times. They then simulated light-curing a posterior restoration by shining the light onto the posterior sensor (upper left second molar). The participants then received the following to help them optimize their light polymerization technique:

1. Proper hand positioning was demonstrated.
2. The mannequin head was adjusted for better access to the restorations.
3. Protective eyeglasses were used so that they could watch the position of the LPU during the procedure.
4. Proper positioning and stabilization of the light-tip using a two-handed technique when using the LPU was demonstrated.

After receiving these specific instructions, the participants were retested using the same protocol and the same LED-LPU as above. During the test procedure, the participants were not allowed to

Table 1. *List of LED-LPUs tested using the checkMARC device, the number of units tested, the range of the mean RE values delivered in 10s, and the type of LPU*

LED-LPU	Number of Units	RE Range J/cm^2	Type
ART L5	2	1.9-9.8	Monowave
Bluephase G2	8	6.1-13.4	Multiwave
Bluephase 16i	2	11.1-15.6	Monowave
Bluephase Style	9	10.5-10.8	Multiwave
Coltolux LED	5	4.2-10.1	Monowave
Celalux 2	6	8.5-12.9	Monowave
D-Lux	7	4.9-15.9	Monowave
DB-686 LED	1	8.9	Multiwave
D1 Broadband DMX	1	12.6	Multiwave
Demi Plus	18	4.9-12.9	Monowave
Delma PM-LED 03	2	16.9-18.1	Monowave
Elipar Freelite	1	6.3	Monowave
Elipar S10	4	9.4-11.8	Monowave
Flashlite 1401	2	7.3-7.6	Monowave
Flashlite Manga	2	10.7-12.6	Monowave
Ledex WL-070	1	13.1	Multiwave
LE Demetron	3	5.1-6.4	Monowave
LED Turbo Victor	1	6.6	Monowave
MD Apollo LED 2000+	4	11.4-29.8	Monowave
MinLED	3	14.1-19	Monowave
Pardigm	2	12.1-12.3	Monowave
Smartlite MAX	4	5.1-6.6	Multiwave
Smartlite IQ2	1	7.7	Monowave
SDI Radii Plus	2	8.1-8.8	Monowave
Spec 3 (Coltene)	1	17.6	Monowave
Simax C-Led	2	18.8-22.3	Monowave
Dr's Light	1	9.8	Monowave
CURE TC-01	1	11.3	Monowave
Woodpecker LED C1	1	12.2	Monowave
Valo Cordless	15	7.4-14.8	Multiwave
Ultra LED	1	4.3	Monowave

Abbreviations: LED, light-emitting diode; LPU, light polymerization unit; RE, radiant exposure.

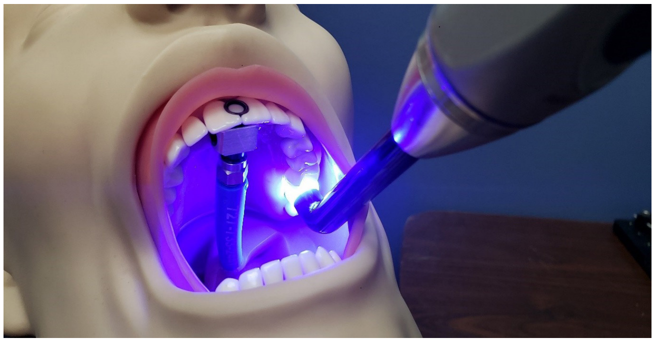

Figure 1. *The MARC Patient Simulator system with a light probe positioned to deliver light to the posterior location (a class I cavity). The anterior sensor, representing the anterior restoration (a class III cavity) is located between the upper central incisors.*

see their real-time results on the computer screen. However, this information helped the test administrator develop personalized instructions based on observed participants' posture and the results displayed on the computer screen. All the MARC PS results were shared with the participants after the test.

For comparative purposes, a control group consisting of eight graduate dental students (four male and four female) were tested in the same way as the participating dental practitioners using one new LPU (Bluephase Style, Ivoclar-Vivadent).

Statistical Analyses

The data was initially tested for normality and homogeneity of variances across the comparison groups (by type of LED-LPU and dental professional). To investigate whether the average RE delivered by dental professionals at the anterior and posterior restorations before and after instructions was different for the LED-LPUs at the three different energy levels (6-7.99 J/cm^2, 8-9.99 J/cm^2, and 10+ J/cm^2), a series of one-way analysis of variance (ANOVA) was conducted.

McNemar tests were used to compare proportions of dental professionals who were able to deliver at least 6 J/cm^2 to the sensors before and after receiving specific instructions. One-sample *t*-tests were used to compare the mean RE values in the study sample to the mean values achieved by the control group. To examine whether the average RE levels increased as a result of the instructions, paired-samples *t*-tests were used. Separate analyses were conducted for the anterior and posterior sensors.

The third and fourth hypotheses were addressed with a series of two-way ANOVAs. To investigate the effect of instructions on increased RE values and type of LED-LPUs on RE values delivered by test subjects, a series of two-way ANOVA was conducted, followed by Fisher *post hoc* multiple comparison tests using a preset alpha of 0.05. The SPSS software version 26 (SPSS Inc, IBM, Somers, NY, USA) was used for all statistical analyses. Type of LED-LPU (monowave vs. multiwave) and the maximum energy levels (6-7.99 J/cm^2, 8-9.99 J/cm^2, and 10+ J/cm^2) were used as between factors in ANOVAs for hypothesis 3. Type of dental professionals (male dentists, female dentists, and dental assistants) and the maximum energy levels (6-7.99 J/cm^2, 8-9.99 J/cm^2, and 10+ J/cm^2) from the LPUs were used as between factors in ANOVAs for hypothesis 4.

RESULTS

Table 1 reports the LED-LPUs tested in addition to their type (monowave vs multiwave) and the ranges for RE values. A wide range of RE was observed among the 113 LPUs with the lowest recorded for ART L5 unit (1.9 J/cm^2) and the highest for the MD Apollo LED 2000+ (29.8 J/cm^2).

The Kolmogorov-Smirnov test for normality indicated that the data were normally distributed (p=0.339). Equality of variances assumption across the comparison groups was tested with Levene test. The result was not significant (p=0.813); thus, the equality of variances was assumed. A power analysis using the G Power program for independent and paired samples *t*-tests revealed that the sample size of 103 could detect a medium effect with the independent samples *t*-tests (Cohen d=0.53) and a small effect with the paired-samples *t*-tests (Cohen d=0.23).

At the initial assessment, 18 of 113 (15.9%) participants used protective glasses, 82 (72.6%) used handheld screens, and 13 (11.5%) used no eye protection. Mean RE values delivered by dental professionals in 10s to the MARC PS anterior and posterior sensors before and after instructions are reported in Figure 2. As can be seen from the figure, the mean RE values delivered at both locations significantly increased in the three groups of LPUs (6-7.99 J/cm^2, 8-9.99 J/cm^2, and 10+ J/cm^2) after receiving instructions. These results were confirmed with the one-way ANOVAs. Omnibus tests were significant at the anterior location before (F[2, 100]=6.77, p=0.002, h^2=0.12) and after (F[2, 100]=7.34, p=0.001, h^2=0.11) receiving instructions. Similarly, the results of ANOVA tests were significant at the posterior location before (F[2, 100]=6.14, p=0.003, h^2=0.13) and after (F[2, 100]=9.87, p<0.001, h^2=0.16). *Post hoc* analyses using the Bonferroni method showed that the group with a mean RE value of 10+ J/cm^2 delivered significantly more energy than the group with a mean RE value of 6-7.99 J/cm^2 in all four instances. Mean RE values delivered by the control group participants in 10s were 9.8 J/cm^2 at the anterior location before instructions and 12.6 J/cm^2 after instructions. At the

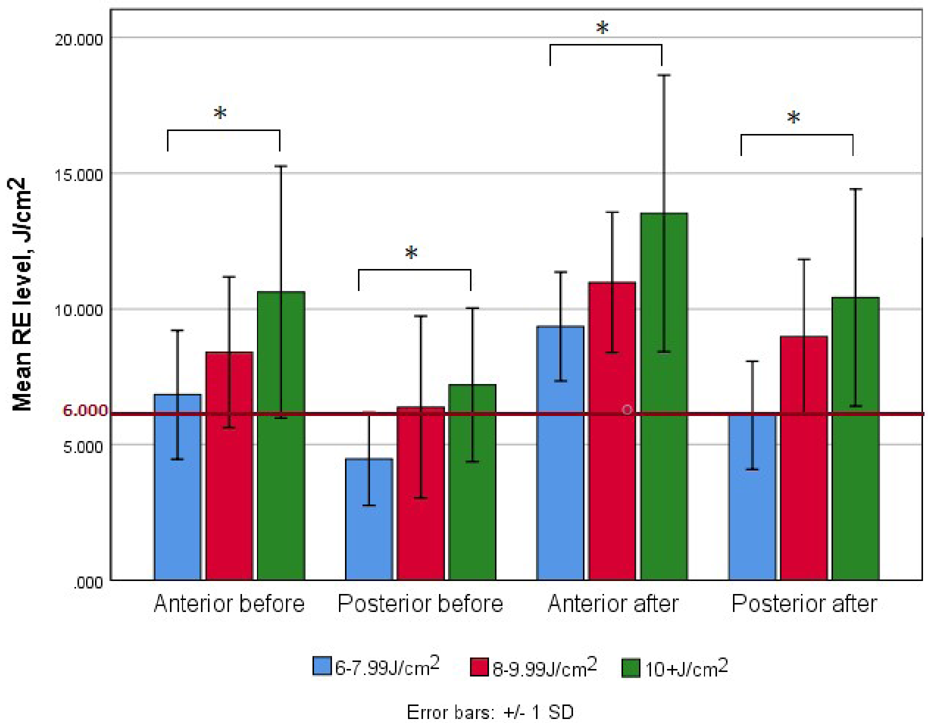

Figure 2. *Mean radiant exposure (RE) values delivered by dental professionals (n=103) to the MARC Patient Simulator simulated restorations. A line is drawn at the 6 J/cm^2 representing the minimum acceptable value. Data were acquired in four sequences: anterior and posterior locations before and after receiving the additional instructions.*
**Statistically significant differences were observed among the three groups at all locations.*

posterior location, a mean value of 9.9 J/cm^2 was recorded before instructions and 11.1 J/cm^2 after instructions. A comparison chart showing the mean RE values of the professionals who were tested and the control group is shown in Figure 3. Mean RE values were similar in the two groups at the anterior location before and after receiving the additional instructions. However, at the posterior location, the mean RE in the study group was lower than in the control group. One-sample *t*-test showed that the difference for the anterior location was not significant (t[102]=-0.59, p=0.56, Cohen d=-0.06 before instructions, and t[102]=-0.60, p=0.549, Cohen d=-0.06 after instructions). However, at the posterior location, significant differences were found with mean RE values being lower in the study group compared with the control group (t[102]=-11.32, p<0.001, Cohen d=-1.11 before instructions, and t[102]=-4.41, p<0.001, Cohen d=-0.44 after instructions).

The percentage of participants delivering the study minimum RE of 6 J/cm^2 for each location is illustrated in Figure 4. Fisher exact tests confirmed that there was no significant difference at the anterior location before (p=0.113, Cramer's V=0.20) and after instructions (p=0.306, Cramer's V=0.11). However, for the posterior location, a significant difference was found between before instructions (p<0.001, Cramer's V=0.40) and after instructions (p<0.001, Cramer's V=0.55).

The mean RE values delivered by monowave and multiwave LED-LPUs used by the study participants are presented in Figure 5. At the anterior location, before the instructions, the mean RE values delivered by dental professionals differed substantially between the monowave and multiwave LED-LPUs (F[1, 97]=4.01, p=0.046, partial h^2=0.041). The multiwave LED-LPUs exhibited a higher average RE level (10.82±5.31) compared with the monowave units (8.78±3.28); this finding was true across all three groups as the interaction effect was not statistically significant (F[2,97]=0.40, p=0.674, partial h^2=0.008). Nevertheless, after the instructions, there was no notable difference in the average RE values between the monowave and multiwave LED-LPUs (F[1, 97]=0.16, p=0.155, partial h^2=0.021). This finding was similar across all three groups of lamps with different maximum energy levels (F[2, 97]=0.18, p=0.834, partial h^2=0.004).

In contrast, for the posterior location, significant interaction effects between the type of LED-LPU and all three groups were detected before the participants received the additional instructions (F[2, 97]=3.77,

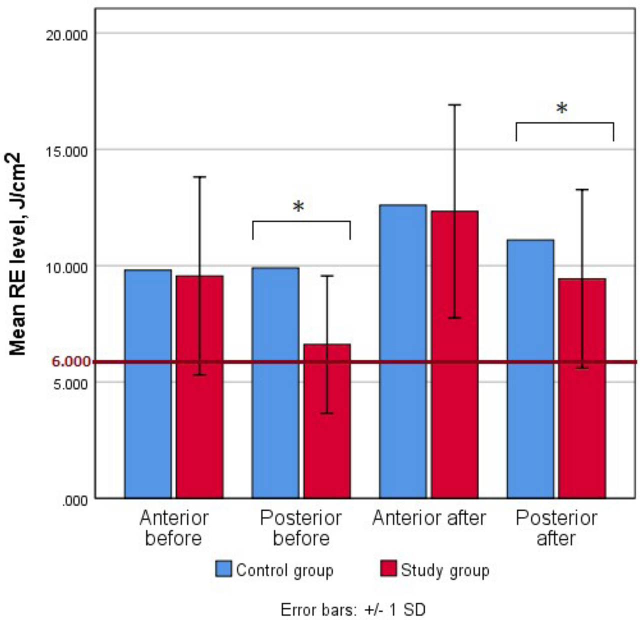

Figure 3. *Percentage of participants who delivered (before and after receiving additional instructions) 6 J/cm² to each restoration location.*
**Statistically significant differences were observed at the posterior location, before and after receiving the additional instructions. RE, radiant exposure.*

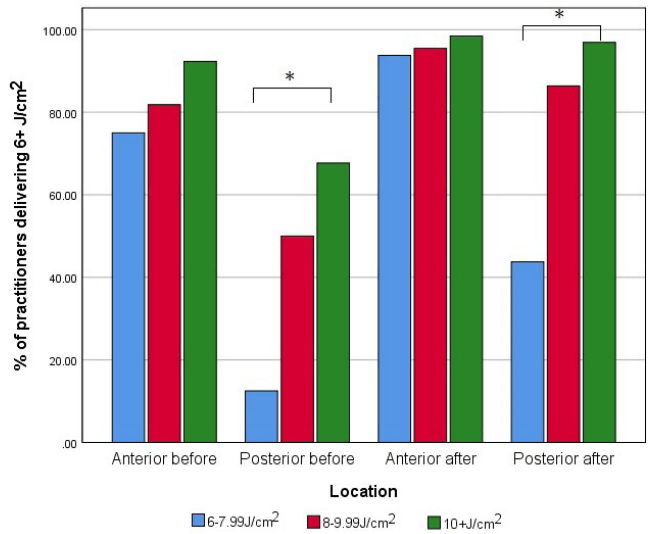

Figure 4. *Mean radiant exposure (RE) values of the control group and tested professionals delivered to the MARC Patient Simulator. A line is drawn at the 6 J/cm² minimum acceptable value. Data were acquired in four sequences: anterior and posterior locations before instructions and anterior and posterior locations after receiving the additional instructions.*
**Statistically significant differences were observed at the posterior location, at the baseline, before the instructions.*

p=0.027, partial h^2=0.07). It was revealed that there was a significant difference in the average RE values delivered by dental professionals to the posterior location before receiving the additional instructions for monowave LED-LPUs with a maximum energy of 6-7.99 J/cm² compared with the units with a maximum energy level of 10+ J/cm². Specifically, the average RE for monowave units with 6-7.99 J/cm² (8.91±1.37) was significantly lower than monowave units with 10+ J/cm² (13.15±0.68;, p=0.019).

At the posterior location after the instruction, the average RE delivered by dental professionals differed greatly between monowave and multiwave LED-LPUs (F[1, 97]=5.01, p=0.028, partial h^2=0.049). Multiwave units exhibited a higher average RE (10.39±4.36) compared with monowave units (8.84±3.38). This finding was true across all three groups as the interaction effect was not significant (F[2,97]=1.03, p=0.360, partial h^2=0.021).

To determine whether there were differences between the mean RE values delivered by the male dentists, female dentists, and dental assistants, a series of two-way ANOVAs were conducted. The results showed that for both anterior and posterior locations before and after instructions, the mean RE delivered by three different types of dental professionals was not significantly different, and this finding was true across all three groups. The means and standard deviations for the mean RE values for each dental professional group and their corresponding LED-LPUs' RE level groups are displayed in Figure 6.

DISCUSSION

A single administrator completed the entire study, which substantially reduced interobserver variability and performance bias while, at the same time, enabling the test administrator to evaluate internal validity during the entire research process. The wide range of RE values for the 113 LED-LPUs reported in Table 1 is concerning. It is difficult to fathom that in the same metropolitan area, one dentist is providing his or her patients with posterior composite restorations polymerized with an LED-LPU that can only deliver 1.9 J/cm² in 10s, when another dentist is using a different LED-LPU unit that is capable of delivering 29.8 J/cm². No matter what resin composite material these dentists are using, there is no doubt that the quality of posterior RBC restorations produced by these two LED-LPUs will be different from the manufacturer's expectations. This was not related to variability in their clinical technique but was instead due to a significant difference in RE values delivered with one unit capable of delivering 10 times more RE than the other. This finding is a strong indication that there is a need for the dental governing bodies to consider regulation of LPUs used in private practices

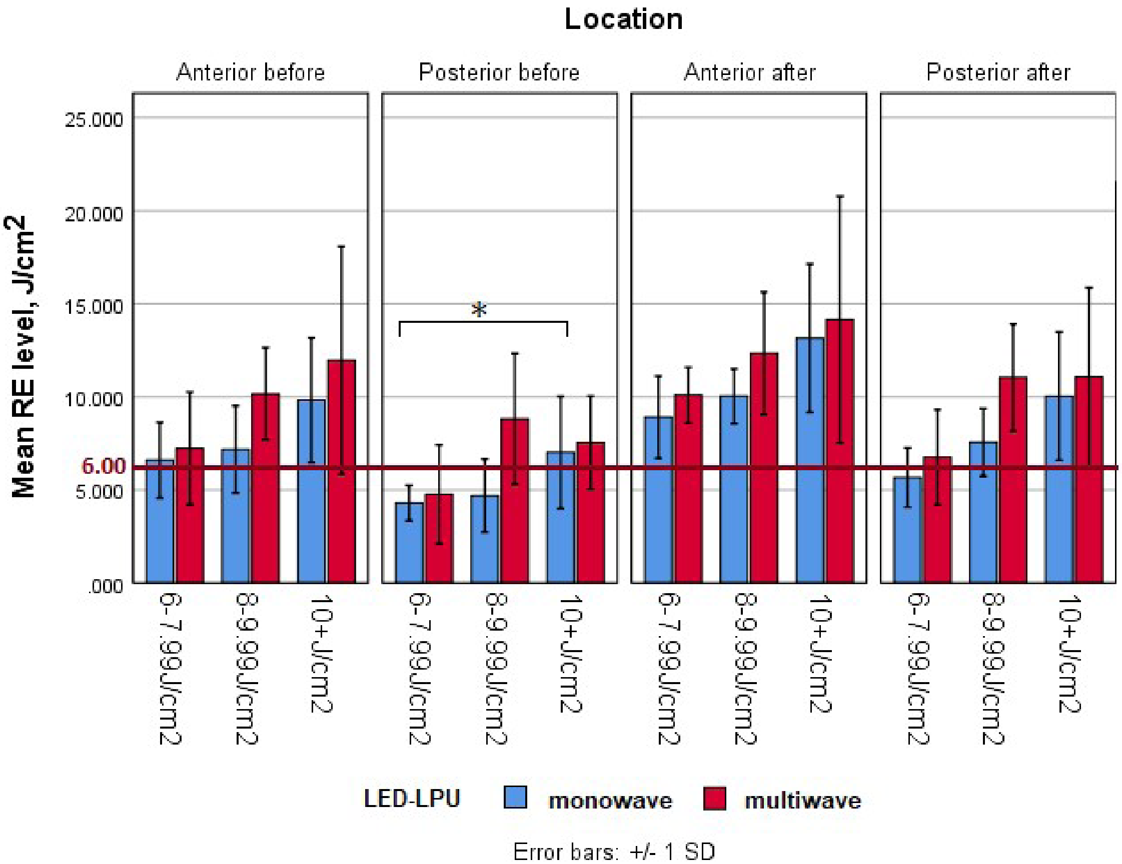

Figure 5. *Mean radiant exposure (RE) values of the control group and tested professionals delivered to the MARC Patient Simulator. A line is drawn at the 6 J/cm² minimum acceptable value. Data were acquired in four sequences: anterior and posterior locations before instructions and anterior and posterior locations after receiving the additional instructions. *Statistically significant differences were observed at the posterior location, before receiving the additional instructions.*

to ensure proper polymerization of posterior RBC restorations.

The first research hypothesis that all dental professionals who participated in the study could deliver at least 6 J/cm² to simulated anterior and posterior restorations in the 10s was rejected. Although the majority (87.3%) of participants delivered 6 J/cm² to the anterior restoration before receiving additional instructions, only 55.3% (57 dental practitioners) were able to deliver 6 J/cm² at the posterior location. However, after receiving specific instructions, only 2% of participating dental professionals failed to deliver at least 6 J/cm² to the anterior sensor, and 13.6% of participants were unable to deliver 6 J/cm² to the posterior sensor. These results corroborate previous studies that used students and standardized LPUs to assess the effects of instructions on improved polymerization efficiency using the MARC PS.[39-47] Of note, the initial assessment revealed that 10 LED-LPUs (8.8%) used in dental offices could not deliver a sufficient irradiance (600 mW/cm²) to deliver 6 J/cm² in 10s. The rationale for using the 10s exposure time was that the instructions for use from many manufacturers of resin composites recommend a 10s exposure for the A2 shade of their materials.[62,63] Some manufacturers[63] are advocating the exposure time based on the LED-LPU ability to deliver at least 500 mW/cm², or 5 J/cm² in 10s. Thus, a minimum RE of 6 J/cm² was used in this study, and it should be noted that it is much less than the 16 J/cm² recommended in the *Phillips' Science of Dental Materials* textbook.[30]

The second research hypothesis that the average RE levels delivered to the simulated anterior and posterior restorations would significantly increase as a result of the participants receiving instructions was accepted. The participants substantially improved the mean RE values they delivered to simulated anterior and posterior restorations as a result of the instructions they received by 22.5% and 30%, respectively. Interestingly, the participants with LED-LPUs that could deliver

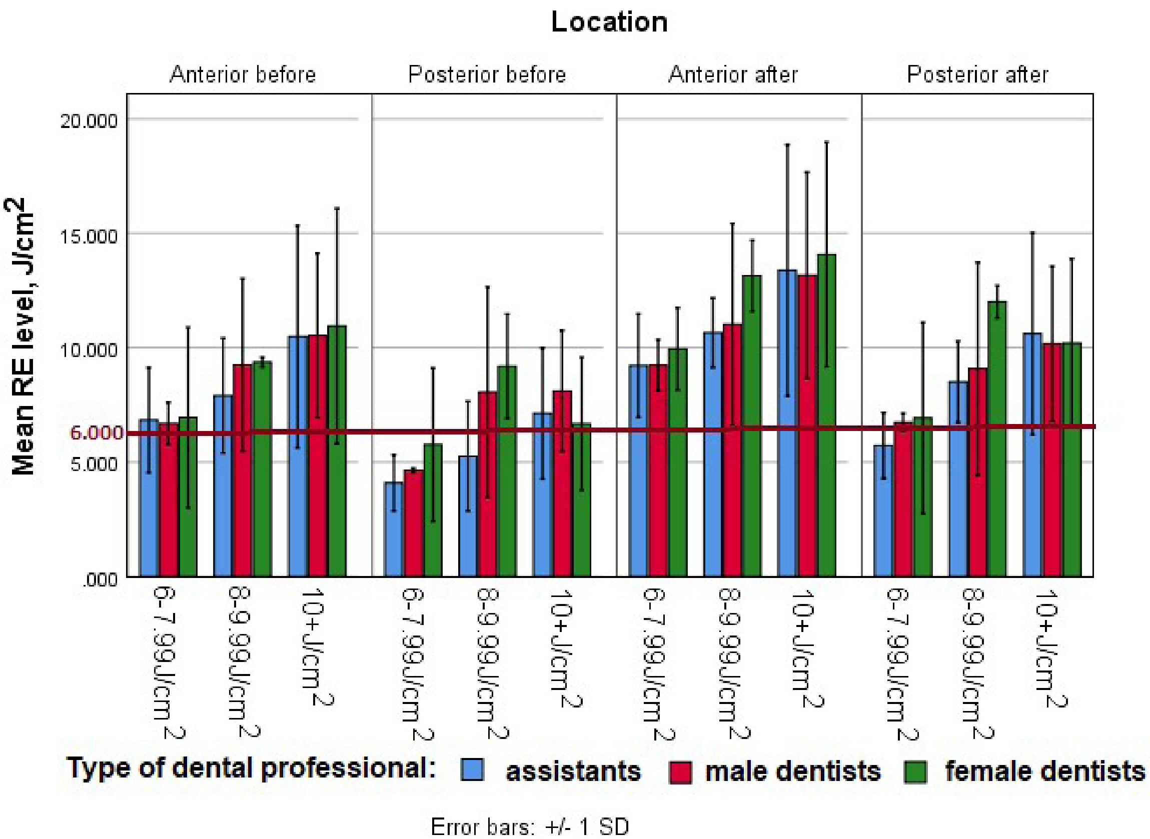

Figure 6. *Mean radiant exposure (RE) values of the male dentists, female dentists, and dental assistants delivered to the MARC Patient Simulator. Data were acquired in four sequences: anterior and posterior locations before instructions and anterior and posterior locations after receiving additional instructions. No significant differences were observed.*

6-7.99 J/cm^2 of RE could not deliver 6 J/cm^2 at the baseline to the posterior restoration, where just 12.5% of test subjects were able to deliver at least 6 J/cm^2. This suggests that LED-LPUs that deliver between 600 and 800 mW/cm^2 should be used for exposure durations that are longer than 10s.

The rationale to use one control LED-LPU to assess the light-curing skills of graduate students was to limit the number of variables. Therefore, the focus was on the light-delivering technique not the LED-LPU. Although the control group participants had no previous experience using the MARC PS system, they exhibited much higher awareness of the importance of adequate light-polymerization, perhaps because they were graduate students who were working on various research projects that involved composite polymerization.

The third research hypothesis that the participants using multiwave or monowave LED-LPUs would deliver a similar RE to simulated restorations was rejected. The multiwave LED-LPUs outperformed monowave LED-LPUs within the same RE range at all measuring points. However, a statistically significant difference between multiwave and monowave units has been observed in only one group (8-9.99 J/cm^2) at the posterior restoration before the instructions. It is indicative that participants using multiwave LED-LPUs delivered substantially higher average RE. However, the number of monowave LED-LPUs was 1.6 times bigger than the number of multiwave LED-LPUs, which may have affected this observation. It could be speculated that multiwave LPUs exhibited higher average RE as those units represented third-generation LED-LPUs that were recently introduced. Furthermore, some multiwave LED-LPUs were used in a standard mode (e.g., Valo, Ultradent South Jordan, UT, USA), thus, reducing their impact in this group.

The fourth research hypothesis that the male dentists, female dentists, and dental assistants would deliver a similar RE was accepted. Interestingly, female dentists exhibited the highest consistency in the RE values they delivered when using LED-LPUs that could deliver 8-9.99 J/cm^2.

The mean RE values delivered to the MARC PS represented the RE that restorations would likely receive in 10s in the participating dental practices. The initial pre-instruction RE values were always lower in comparison to those achieved after receiving the additional instructions and training. One explanation is that many participants (84.1%) initially used the LED-LPU without protective glasses and did not watch what they were doing when using the LED-LPU. In addition, some participants were somewhat apprehensive about performing the procedure; however, during the second and third attempts, they became more relaxed, and this was observed in the improved RE values. After receiving individualized instructions on proper light-curing technique, which included mandatory use of protective glasses and watching the position of the light guide, the participants, on average, delivered significantly higher RE levels to the MARC PS. All the LED-LPUs were tested without an infection control barrier because some practitioners were not routinely using a barrier.

It is concerning that so many dental professionals initially did not use adequate blue-light blocking eye protection. Blue light is transmitted through the ocular media and absorbed by the retina. Chronic exposure to low levels of blue light has been reported to cause retinal damage.[64] When these glasses are used, the clinician can safely watch what he or she is doing when light-curing, which will improve the amount of light delivered to the restoration.[65] Thus, a prudent practitioner will use the appropriate blue-light blocking glasses when operating the curing light.[12]

To improve consistency, all LED-LPUs were tested in their standard mode for 10s, regardless of their ability to deliver a higher irradiance in a different setting. Although the MARC PS sensors are 4 mm in diameter, it was observed that the majority of LED-LPUs tested had an external light-tip diameter between 8 and 10 mm. This discrepancy, along with the LED-LPUs beam profiling features, enabled some LED-LPUs to generate much higher mean RE values. Thus, in certain instances, some RE values were between 10% and 25% higher than the value reported by the checkMARC device. The explanation for this phenomenon could be because the checkMARC measures the entire light output.

In contrast, the MARC PS only measures the light received by a 4-mm sensor. Some lights did not deliver a homogeneous irradiance output. Instead, they delivered a higher irradiance from the center of the light-tip and thus produced higher MARC PS values.

The significant difference in the amount of RE delivered at the anterior and posterior locations may be related to LPU's tip design and the limited practitioners' ability to access the posterior restorations. The design of the light probe can cause a substantial challenge where there is limited interocclusal space. Furthermore, the limited ability to observe the position of the LED-LPU's tip creates a challenge in keeping the light-tip precisely over and perpendicular to the restoration. The MARC PS results revealed that the LPUs with a more curved light-tip delivered, on average, lower RE values to the posterior restoration, in comparison to the LPUs with a less curved light and lower profile tip. The phenomenon could be explained that a curved light probe usually needs more interocclusal space to be positioned over the tooth. The same pattern has been observed by the control group using the Bluephase Style LPU, which has a curved low-profile light-tip.

This study may have some inclusion issues. Participation in this study was voluntary, and the main excuse for those practices that declined to participate was their inability to find time to accommodate the research. Those dental practices who knew that they used lower quality LPUs or those who doubted their skills in placing RBCs might have decided not to participate. The study exhibited standardized protocols for data collection and data entry. Another potential limitation of this study was the use of a 10s radiant exposure with the MARC PS device. Although 10s is the exposure time recommended by many manufacturers, if a 20s radiant exposure had been used, the results would have been significantly different.

This study supports the view that significant improvement can occur in the amount of RE delivered after dental practitioners received specific instructions on light curing and used protective eyewear and a two-hand polymerization technique to stabilize the light-tip during the polymerization. Future research could include dentists practicing in rural locations to explore if they differ from urban practitioners in this respect. Because a significant number of participants delivered RE values less than 6 J/cm^2, and 8.8% of the LPUs tested could not deliver a RE of 6 J/cm^2 to the checkMARC in 10s, continuing education courses that address the importance of light polymerization in dentistry are recommended.

CONCLUSIONS

Within the limitations of this study, for dental professionals using their own LPU for 10s, the following was concluded:

1. At the baseline, 12.7% of participants failed to deliver at least 6 J/cm^2 to the anterior simulated restoration, and 44.7% of participants failed to deliver 6 J/cm^2 to the posterior simulated restoration; after receiving additional instructions and training, only 1.9% could not deliver 6 J/cm^2

to the anterior, and 13.6% failed to deliver 6 J/cm^2 to the posterior simulated restoration.

2. Following the instructions, the mean RE values delivered by participants to the simulated anterior and posterior restorations increased by 22.5% and 30%, respectively.
3. Multiwave LED-LPUs outperformed monowave LED-LPUs at all measuring points.
4. The mean RE values delivered by the male and female dentists and by dental assistants were not significantly different.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of the University of Toronto Research Ethics Board. The approval code issued for this study is 14-063.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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