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Influence of Emission Spectrum and Irradiance on Light Curing of Resin-Based Composites

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Clinical Relevance

Clinicians should be aware that while broad-spectrum LED curing lights can enhance the properties at the top of a restoration made of resin composites that contain "alternative" photoinitiators, the use of these lights could result in inferior properties at the bottom, since little violet light reaches this area of the restoration.

SUMMARY

Purpose: This study examined the influence of different emission spectra (single-peak and broad-spectrum) light-curing units (LCUs) delivering the same radiant exposures at irradiance values of 1200 or 3600 mW/cm^2 on the polymerization and light transmission of four resin-based composites (RBCs).

Methods and Materials: Two prototype LCUs that used the same light tip, but were either a single-peak blue or a broad-spectrum LED, were used to deliver the same radiant exposures to the top surfaces of the RBCs using either standard (1200 mW/cm^2) or high irradiance (3600 mW/cm^2) settings. The emission spectrum and radiant power from the LCUs were measured with a laboratory-grade integrating sphere coupled to a spectrometer, and the light beam was assessed with a beam profiler camera. Four RBCs (Filtek Supreme Ultra A2, Tetric EvoCeram A2, Tetric EvoCeram T, and TPH Spectra High Viscosity A2) were photoactivated using four different light conditions: single-peak blue/standard irradiance, single-peak blue/high irradiance, broad-spectrum/standard irradiance, and broad-spectrum/high irradiance. The degree of conversion (N=5) and microhardness at the top and bottom of 2.3-mm-diameter by 2.5-mm-thick specimens (N=5) were analyzed with analysis of variance and Tukey tests. The real-time light transmission through the RBCs was also measured.

Results: For all light conditions, the 2.3-mm-diameter specimens received a homogeneous

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DOI: 10.2341/16-349-L

irradiance and spectral distribution. Although similar radiant exposures were delivered to the top surfaces of the RBCs, the amount of light energy emitted from the bottom surfaces was different among the four RBCs, and was also greater for the single-peak lights. Very little violet light (wavelengths below 420 nm) reached the bottom of the 2.5-mm-thick specimens.

The degree of conversion and microhardness results varied according to the RBC ($p<0.05$). The RBCs that included alternative photoinitiators had greater microhardness values at the top when cured with broad-spectrum lights, while at the bottom, where little violet light was observed, the results were equal or higher when they were photoactivated with single-peak blue lights. With the exception of the microhardness at the top of TPH, equivalent or higher microhardness and degree-of-conversion values were achieved at the bottom surface when the standard (1200 mW/cm^2) irradiance levels were used compared to when high irradiance levels were used.

Conclusions: Considering the different behaviors of the tested RBCs, the emission spectrum and irradiance level influenced the polymerization of some RBCs. The RBCs that included alternative photoinitiators produced greater values at the top when cured with broad-spectrum lights, while at the bottom, results were equal or higher for the RBCs photoactivated with single-peak blue lights.

INTRODUCTION

Camphorquinone is the most commonly used photoinitiator in resin-based composites (RBCs), but it has a yellow color that may influence the final color of the restoration.[1] This can be problematic if the patient has bleached teeth or otherwise requires a light-colored restoration. Consequently, some resin manufacturers have started to use "alternative" photoinitiators, such as Lucirin TPO and Ivocerin. These photoinitiators do not impart such a yellow color to the final restoration, but they are most reactive to lower wavelengths of light[2] close to 410 nm compared to camphorquinone, which is most sensitive to light at 468 nm, or below 320 nm.

Light-curing units (LCUs) that use light-emitting diodes (LEDs) rather than halogen lights produce a relatively narrow wavelength of light and deliver little below 420 nm. Since they may not be able to adequately activate these alternative photoinitiators, some manufacturers have included in their LCUs several different LED chips that emit light at different wavelengths, thus producing a broader emission spectrum.[3,4] However, it is difficult to achieve a uniform distribution of light at the tip of the LCU, and this inhomogeneity can lead to nonuniform polymerization of dental restorations.[5-8]

Another trend is to try to make clinical procedures faster. Instead of using a 40-second light exposure time, some manufacturers claim that their LCUs deliver such a high irradiance that they can adequately polymerize RBC restorations in as little as one second. However, studies have shown that light-curing RBCs for short exposure times is not ideal.[9-11] This is of concern because inadequate photoactivation of the RBC can negatively affect the properties of the restoration, resulting in a lower degree of double-bond conversion and inferior mechanical properties.[12-14] Also, the degree of conversion of the resin has a direct correlation with biocompatibility of the RBC restoration in the mouth.[15] Moreover, the irradiance of the LCU used in the photoactivation of the RBC may affect the polymerization kinetics, and a rapid polymerization reaction may increase the polymerization contraction stresses and have detrimental effects on the restoration.[16,17]

Since there are many different types of LCU available, dentists should be aware of differences that exist among units and the impact these differences can have on the RBC. They should know when it is appropriate to use each type of LCU.[18,19] To provide the dentist with this information, this study aimed to verify the influence on the polymerization of four different RBCs with different emission spectra from single-peak and broad-spectrum LED units, which delivered either a standard irradiance that is typical of most contemporary LCUs, or a high irradiance typical of a powerful LCU. The null hypotheses were the following:

1) There will be no difference between the degree of double-bond degree of conversion and the Knoop microhardness of RBCs achieved when light cured with the single-peak blue or the broad-spectrum curing lights.
2) There will be no difference between the degree of double-bond conversion and microhardness of RBCs when light cured under the standard irradiance, or the high-irradiance conditions.
3) There will be no correlation between the degree of double-bond conversion and Knoop microhardness

values of RBCs when light cured using the different exposure conditions.

METHODS AND MATERIALS

Four RBCs were used in this study: Filtek Supreme Ultra—shade A2B (3M ESPE, St Paul, MN, USA), Tetric EvoCeram —shade A2 (Ivoclar Vivadent, Amherst, NY, USA), Tetric EvoCeram—shade T (Ivoclar Vivadent), and TPH Spectra High Viscosity—shade A2 (Dentsply, Milford, DE, USA). They were photoactivated using either a custom-designed single-peak blue light or a broad-spectrum light, both made by Ultradent (South Jordan, UT, USA). The optics (lenses) in both units were identical, both had a 9.6-mm tip diameter, and only the LED emitters were different. The electrical current to the LED emitters of both LCUs could be altered by the user, thus allowing the units to deliver various irradiance levels.

Characterization of the LCUs

The emitted radiant power and emission spectrum were measured through a 2.3-mm-diameter aperture into a FOIS-1 integrating sphere (Ocean Optics, Dunedin, FL, USA) coupled to the USB 4000 fiber-optic spectrometer (Ocean Optics). Before the measurements, the system was calibrated using an LS-1-CAL-INT calibration lamp (Ocean Optics). For each light condition, five measurements of the spectral radiant power emitted between 350 and 550 nm were made. Using results from the integrating sphere, the electrical current to the LED chip was adjusted so that the same radiant exposure was delivered in four exposure conditions: 1) single-peak blue light with standard irradiance (SS), 2) single-peak blue light with high irradiance (SH), 3) broad-spectrum multipeak light with standard irradiance (MS), and 4) broad-spectrum multipeak light with high irradiance (MH).

As previously described,[20] to assess the radiant power distribution across the LCU tip, the beam profile analysis was made using a charge-coupled device (CCD) digital camera with a 50-mm-focal-length lens (SP620U, Ophir-Spiricon, Logan, UT, USA) that was fixed at a predetermined distance from the diffusing surface of a translucent ground-glass target (DG2X2-1500, Thor Laboratories, Newton, NJ, USA). A custom-made blue filter (International Light Technologies, Peabody, MA, USA) was used to flatten the spectral response of the CCD camera. The photonic count received by each camera pixel was calibrated with BeamGage version 6.6 software (Ophir-Spiricon). The effect of the ambient light was eliminated before the data collection by using the UltraCal feature in the BeamGage software.

The image received by the camera was collected using the BeamGage software 10 seconds after activating the LCUs using the standard irradiance conditions and three seconds after activating the LCUs under the high-irradiance conditions. Color-coded and calibrated irradiance images were generated using the mean values of emitted radiant power that had been previously collected. The graphics software program Origin Pro version 9.1 (OriginLab, Northampton, MA, USA) was used to scale the two-dimensional images that were then visually compared.

Degree of Conversion

Degree of double-bond conversion measurements were made in gray opaque molds that were 2.3 mm in diameter and 2.5 mm in height. The molds were filled with uncured RBCs and placed directly over the diamond at the center of the Golden Gate Attenuated Total Reflectance (ATR) platform (Specac, Orpington, Kent, UK) attached to a Tensor 27 Mid IR FT-IR spectrometer (Bruker, Billerica, MA, USA). A Mylar strip was placed over the top of the uncured resin and pressed flat with a glass slab. The slab was removed and the specimen was exposed for 15 seconds using the standard irradiance level or five seconds using the high irradiance level. These exposure times delivered the same radiant exposures to the RBCs. The mid IR spectra were collected for five seconds before light curing and were recorded continuously in real time for four minutes at a resolution of eight wavenumbers and collection rate of two scans per second. Five specimens were made with each RBC and each light condition for a total of 80 specimens.

Knoop Microhardness

After the degree-of-conversion analysis, the specimens were removed from the ATR platform. Twenty-four hours after light curing the specimen, three Knoop microhardness indentations were made in the top and the bottom of each specimen, using a load of 15 gf for eight seconds in a microhardness-testing device (HM 123, Mitutoyo, Kawasaki, Kanagawa, Japan).

Light Transmission

The FOIS-1 integrating sphere coupled to the USB 4000 fiber-optic spectrometer was used to measure

Table 1: *Emitted Radiant Power (mW), Calculated Irradiance (mW/cm^2), and Radiant Exposure (J/cm^2) ± Standard Deviations From Each of the Four Light Conditions: Single Standard, Single High, Multi Standard, and Multi High*

Polymerization Mode	**Power** (mW)	**Irradiance** (mW/cm^2)	**Radiant Exposure** (J/cm^2)
Single standard	49.6 ± 0.7	1193.8 ± 17.6	17.9 ± 0.26
Single high	149.9 ± 0.7	3607.9 ± 16.6	18.04 ± 0.08
Multi standard	51.1 ± 0.1	1229.9 ± 3.2	18.4 ± 0.05
Multi high	150.1 ± 1.1	3612.7 ± 26.0	18.1 ± 0.13

the light transmission through the RBC. The RBCs were inserted in a single portion into the same gray opaque molds used for the degree-of-conversion analysis and covered with Mylar strips. Then they were pressed between two glass mixing slabs to produce flat top and bottom surfaces. These molds, now filled with uncured RBC, were placed at the aperture of the integrating sphere and photoactivated at 0-mm distance. SpectraSuite software (Ocean Optics) was used to record, in real time, the spectral radiant power transmitted through each RBC.

After the transmitted spectral radiant power had been measured, the light beam profile through the cured specimen was measured using the beam profiler camera with a 50-mm-focal-length lens (SP620U, Ophir-Spiricon) and a custom-made blue filter (International Light Technologies). The molds filled with the cured RBC were placed at a fixed distance from the camera, and the LCU tip was placed in contact with the molds. Then the LCU was activated, and the light beam transmitted through the cured RBC was examined. Narrow-band-pass interference filters that had a maximum bandwidth centered at 400 or 460 nm and a full-width half-maximum tolerance of 10 nm (Edmund Industrial Optics, Barrington, NJ, USA) were used to collect separate beam profile images of the transmitted violet and blue lights. The images were collected using BeamGage version 6.6 software (Ophir-Spiricon). Only the high-irradiance-level light conditions were beam profiled through the different RBCs.

Statistical Analysis

Analysis of variance, followed by the Tukey *post hoc* multiple comparison test (α=0.05), was applied. To determine if there was a statistically significant difference between the degree of conversion and Knoop microhardness obtained under the different light exposure conditions, tests were applied separately for each RBC since each RBC has a different composition. In addition, the Pearson correlation test was applied to verify if there was a correlation between degree of conversion and microhardness measured at the bottom of the specimens.

RESULTS

The emitted radiant power, calculated irradiance, and radiant exposure values from each of the four light conditions are reported in Table 1. The emission spectrum and the wavelength peaks of the four light conditions are shown in Figure 1. The light beam profiles showed that there was a homogeneous distribution of the light through the 2.3-mm aperture (Figure 2) in all cases.

Means and standard deviations of the Knoop microhardness values at the top of the specimens are reported in Table 2. Photoactivation with the SS light resulted in statistically higher hardness values, while photoactivation with the SH light resulted in lower values. Specimens photoactivated with the broad-spectrum lights presented intermediate hardness values. The degree of double-bond conversion and Knoop microhardness values at the bottom are also reported in Table 2. Filtek Supreme Ultra A2 photoactivated with the SS light (single-peak blue

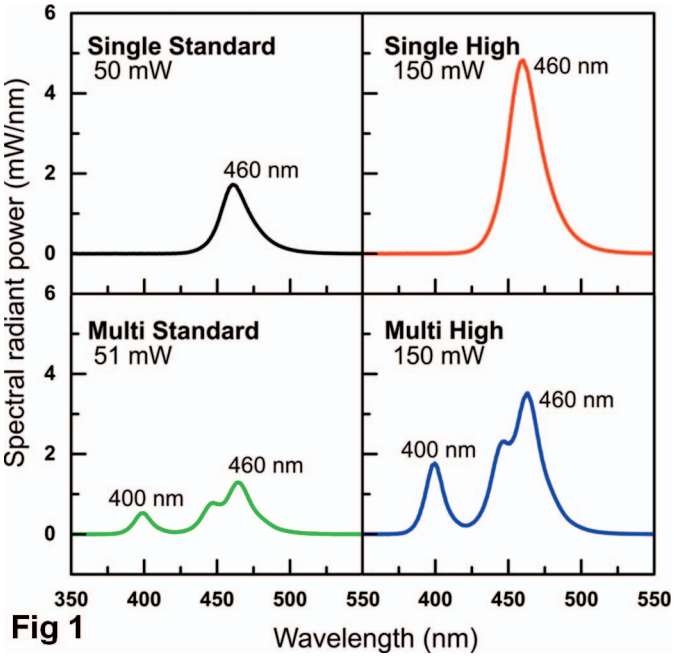

Figure 1. *Emission spectrum, power (mW) and wavelength peaks (nm) from the two lights for each of the four light conditions.*

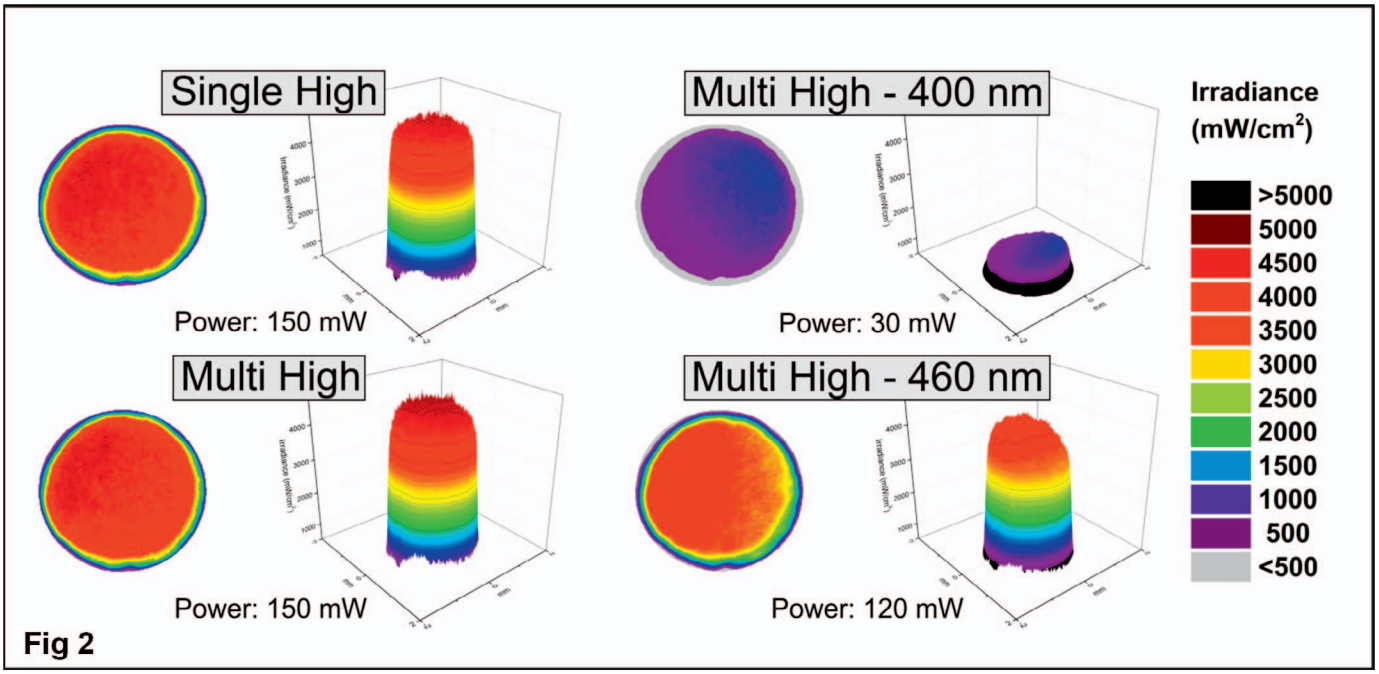

Figure 2. *Two- and three-dimensional light beam profiles of the lights recorded through the 2.3-mm aperture together with the power (mW) and scaled irradiance (mW/cm^2) using the single high (SH) and multi high (MH) light conditions. The images were taken both without a filter and with either a 400-nm or a 460-nm ±5 nm narrow-band-pass filter and scaled using the power values (mW) calculated from the integrated area under the emission spectrum (violet 30 mW, blue 120 mW).*

light with standard irradiance) achieved a significantly higher degree of conversion compared to when the MH light (multipeak light with high irradiance) was used, while, when photoactivated with the SH light (single-peak light with high irradiance) and MS light (multipeak light with standard irradiance), it presented intermediate values. The microhardness at the bottom of the specimen followed the same trends as the degree-of-conversion results.

Specimens of Tetric EvoCeram A2 and Tetric EvoCeram T made at the standard irradiance setting resulted in a higher degree of double-bond conversion values when either the single-peak blue (SS) or the broad-spectrum (MS) light was used. The specimens photoactivated with the SS light showed the highest degree-of-conversion results at the bottom for the Tetric EvoCeram A2, but there was no statistical difference between values obtained with blue light and broad-spectrum light for the Tetric EvoCeram T.

For the TPH Spectra High Viscosity A2, degree-of-conversion and microhardness values were not statistically different for specimens photoactivated with either the single-peak blue or the broad-spectrum lights. However, regarding degree of conversion and microhardness values at the bottom, the use of lower irradiances resulted in higher values, while for the top microhardness, specimens photoactivated with high irradiances presented higher microhardness values. The Pearson correlation test showed a significant linear correlation between the degree-of-conversion and the microhardness values at the bottom for all the RBCs tested (Figure 3).

The real-time light transmission results showed that the emitted radiant power that was measured through the 2.5-mm-thick RBCs was dependent on the choice of RBC and varied from only about 1.5% to 8% of the power received at the top, depending on the RBC and the light condition used (Figure 4). The radiant exposures delivered to the bottom of the specimen are reported in Table 3. Of the emitted power, the violet light emitted from the bottom decreased from about 20% of the total power delivered to the top, to only 2.5% to 8% of the total power that was emitted at the bottom (Figure 5). The light transmission increased with exposure time, and there was more light transmission through the translucent Tetric EvoCeram—shade T. The scaled beam profile images illustrate how little of the violet light reached the bottom of the specimens (Figure 6).

DISCUSSION

Previous studies compared light curing using different designs of single-peak blue and broad-spectrum lights.[21-24] This study allowed better standardization

Table 2: *Means ± Standard Deviations for Degree of Conversion at the Bottom (%) and Knoop Microhardness (KHN) for Each of the Four Light Conditions (ext.)*

	Top Hardness (KHN)				Bottom Hardness (KHN)	
	Filtek Supreme Ultra A2B	Tetric EvoCeram A2	TPH Spectra High Viscosity A2	Tetric EvoCeram T	Filtek Supreme Ultra A2B	Tetric EvoCeram A2
Single standard	85.7 ± 1.3 A	32.0 ± 1.1 B	50.4 ± 2.7 B	36.6 ± 2.7 B	31.6 ± 2.5 A	16.5 ± 0.6 A
Single high	79.3 ± 2.5 C	31.9 ± 1.3 B	63.3 ± 2.5 A	29.8 ± 2.6 C	29.1 ± 2.3 AB	14.7 ± 0.8 B
Multi standard	82.0 ± 1.8 BC	55.1 ± 1.6 A	50.2 ± 2.6 B	49.3 ± 4.2 A	30.2 ± 1.8 AB	15.7 ± 1.1 AB
Multi high	83.0 ± 1.8 AB	55.6 ± 1.7 A	63.0 ± 1.5 A	50.2 ± 4.1 A	26.8 ± 0.5 B	16.3 ± 0.2 B

*Statistical differences between light conditions are described with superscript letters, the same letters within a column indicate no significant difference in the value

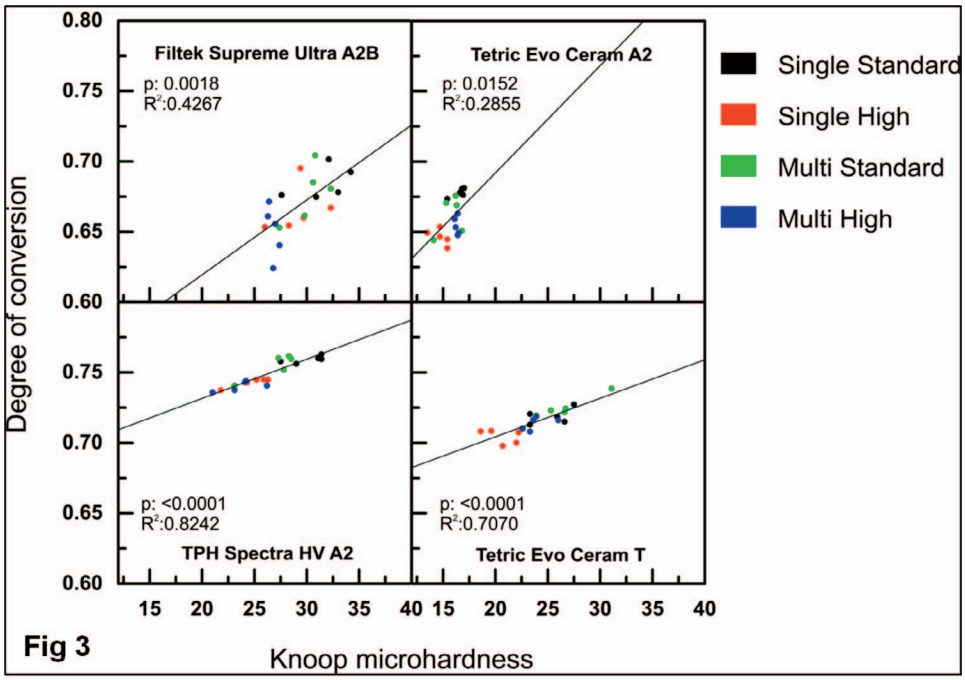

Figure 3. *Scatter graph showing the correlation between Knoop microhardness and degree of conversion for the four resin-based composites for each of the four light conditions (p- and R^2-values indicated for the Pearson correlation test).*

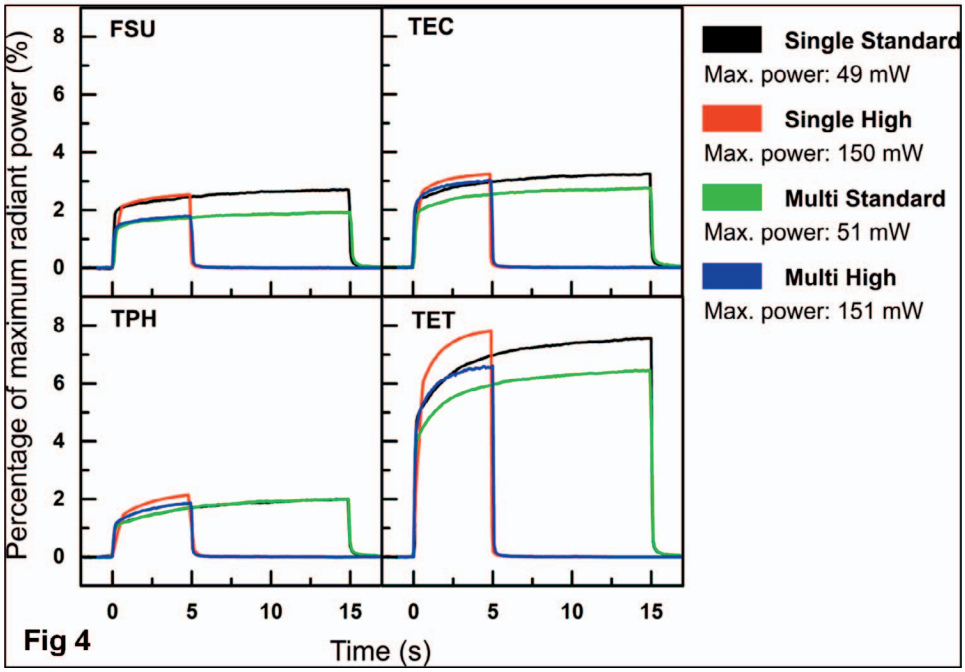

Figure 4. *Percent of maximum power transmitted in real time through the 2.5-mm-thick specimens for each of the four light conditions and for Filtek Supreme Ultra—shade A2B, Tetric EvoCeram—shade A2, Tetric EvoCeram—shade T, and TPH Spectra High Viscosity—shade A2. For TPH, the green line (MS) overlies the black line (SS). Note how the light transmission through the resin-based composites increased with exposure time.*

Table 2: *Extended.*

	Bottom Hardness (KHN)		Degree of Conversion at the Bottom (%)			
	TPH Spectra High Viscosity A2	Tetric EvoCeram T	Filtek Supreme Ultra A2B	Tetric EvoCeram A2	TPH Spectra High Viscosity A2	Tetric EvoCeram T
Single standard	30.1 ± 1.8 A	25.3 ± 1.9 A	68.5 ± 1.2 A	67.8 ± 0.3 A	75.9 ± 0.3 A	71.9 ± 0.6 AB
Single high	24.7 ± 1.8 B	20.6 ± 1.5 B	66.6 ± 1.7 AB	64.7 ± 0.6C	74.3 ± 0.3 B	70.4 ± 0.5 C
Multi standard	27.0 ± 2.2 AB	26.7 ± 2.7 A	67.7 ± 2.0 AB	66.2 ± 1.4 B	75.5 ± 0.9 A	72.5 ± 0.8 A
Multi high	23.7 ± 1.9 B	23.9 ± 1.3 AB	65.1 ± 1.9 B	65.5 ± 0.6 BC	74.0 ± 0.3 B	71.4 ± 0.5 BC

of the light conditions because both lights used the same tip and construction, with changes only in the emission spectra from the LED emitters. The four light exposure conditions delivered similar radiant exposures (Table 1), and the standard and high radiant powers were similar for the single-peak blue and broad-spectrum lights. The shapes of the emission spectra was the same for the blue lights, with peaks at 460 nm, and for the broad-spectrum lights, with peaks at 400 and 460 nm at both settings (Figure 1). For all conditions, the beam profile of the lights showed a homogeneous irradiance distribution through the 2.3-mm aperture. This is relevant since it is known that the distribution of light can be inhomogeneous across the light tip, and this inhomogeneity may affect resin polymerization.[6,18,25] The distributions of the violet and blue light components from the LCUs were also homogeneous, as seen in beam profile images taken through the 400- and the 460-nm narrow-band-pass filters (Figure 2).

The RBCs achieved different microhardness values, as observed in Table 2, and this can also be noted observing the different distributions on the scatter graphs (Figure 3). Tetric EvoCeram A2 achieved the lowest microhardness values, probably due to the different formulation of this product. All the RBCs presented lower microhardness values than expected at the bottom of the specimens. This likely occurred due to the optical characteristics of the opaque molds. The 2.5-mm height is more than the increment thickness recommended by the manufacturer, and the opaque gray molds prevented any light transmission. This should not be considered a limitation of the study because the aim was to measure not the depth of cure of the RBCs but rather the influence of the different exposure conditions on their photoactivation at a clinically relevant thickness (2.5 mm).

The first null hypothesis was rejected since using the broad-spectrum lights increased the top microhardness of two RBCs: Tetric EvoCeram A2 and Tetric EvoCeram T. This result is not unexpected since the manufacturer states that both of these RBCs use the alternative photoinitiators and these initiators are activated by the violet light present in broad-spectrum lights. Previous studies have also reported improved properties when RBCs with these alternative photoinitiators are photoactivated with broad-spectrum lights.[23,26] Consequently, it is recommended that broad-spectrum lights should be used to photoactivate RBCs that have alternative photoinitiators because the top microhardness values would be enhanced. This should reduce the wear and better support occlusal loading.

At the bottom of the specimen, there was no difference between microhardness values when the single-peak blue or the broad-spectrum lights were used, even for the RBCs with alternative photoinitiators in their composition. It might be expected that RBCs that include only camphorquinone in their formulation would achieve a higher microhardness when photoactivated with a single-peak LCU compared to that achieved with a broad-spectrum LED unit delivering the same radiant power because more light energy is delivered in the 460 nm region to the CQ from the single-peak LCU. However, there was no difference between RBCs photoactivated with

Table 3: *Radiant Exposure (J/cm^2) Delivered to the Bottom of the Specimens Made of Each of the Four Resin-Based Composites, Using Each of the Four Light Conditions. (Energy Calculated by Integrating the Area Under the Curve of the Real-Time Power Graph and Dividing It by the Area of the Molds)*

	Filtek Supreme Ultra A2B	Tetric EvoCeram A2	TPH Spectra High Viscosity A2	Tetric EvoCeram T
Single standard	0.42	0.54	0.31	1.24
Single high	0.40	0.52	0.32	1.23
Multi standard	0.34	0.48	0.31	1.11
Multi high	0.31	0.51	0.29	1.11

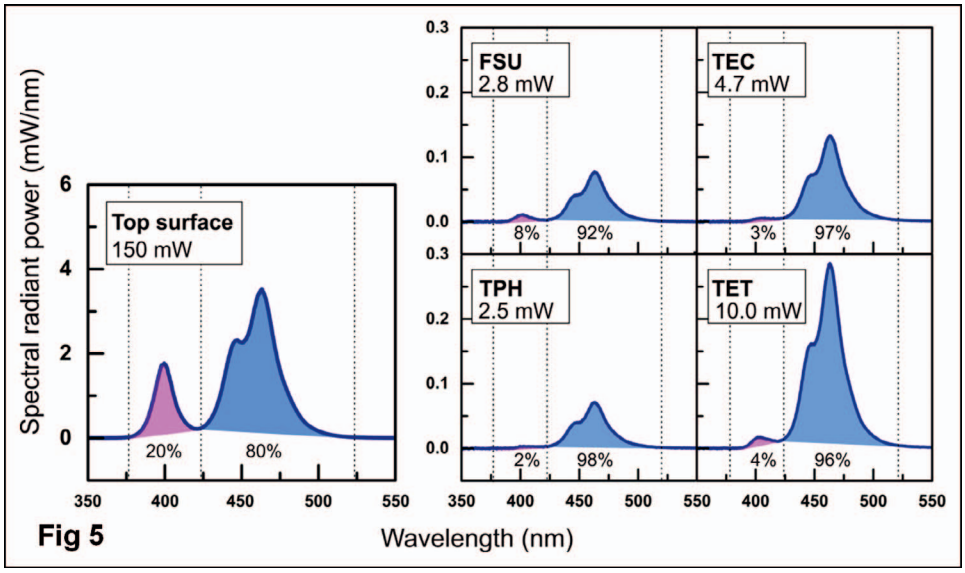

Figure 5. *Radiant power delivered to the top surface and percentage of this radiant power from the violet and blue LEDs that was emitted at the bottom through 2.5 mm of Filtek Supreme Ultra—shade A2B, Tetric EvoCeram—shade A2, Tetric EvoCeram—shade T, and TPH Spectra High Viscosity—shade A2 when using the broad-spectrum high-irradiance light. Note the greater light transmission through the translucent Tetric EvoCeram—shade T and the difference in the transmitted power values compared to what was delivered to the top.*

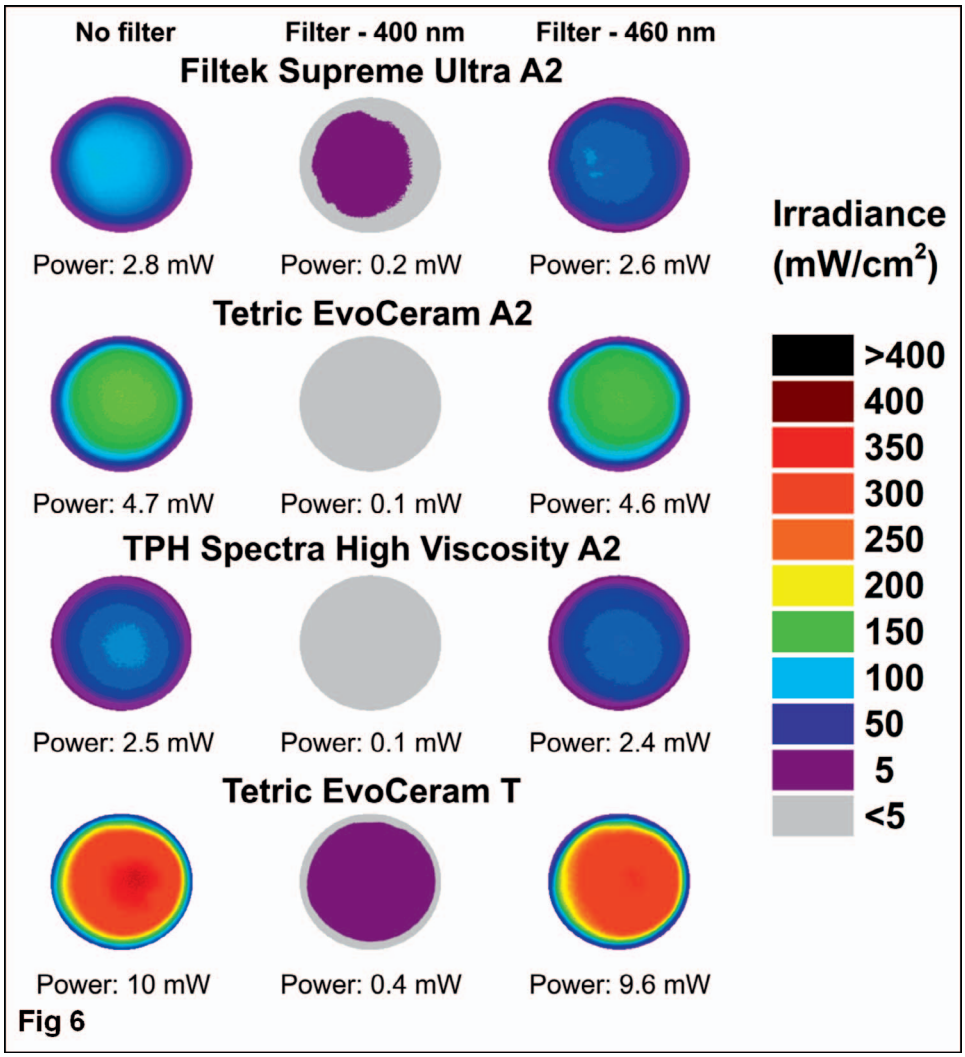

Figure 6. *Scaled two-dimensional irradiance beam profile images viewed through 2.5-mm-thick specimens of the four RBCs. The images were taken without a filter and with either a 400-nm or a 460-nm ±5 nm narrow-band-pass filter. The images were scaled using the power values (mW) calculated from the integrated area under the emission spectrum.*

single-peak or broad-spectrum lights. This probably occurred because more than sufficient radiant exposure was delivered within the blue wavelength range from both lights to photocure the RBCs.

Regarding degree of conversion, except for the Tetric EvoCeram A2 where specimens photoactivated with the SS light achieved a significantly higher degree of double-bond conversion, results were similar to the microhardness outcomes at the bottom, with no difference between specimens photoactivated with single-peak blue and broad-spectrum lights. This likely occurred because all the specimens received more than enough energy at the bottom.

As previously reported, the real-time radiant power transmitted through these four RBCs increased during polymerization [27]; that is, the RBCs became more transparent as they polymerized (Figure 3), but it is still greatly reduced compared to what is delivered to the top surface. Although the curing lights delivered very similar radiant exposures, the radiant power delivered from the broad-spectrum lights is a combination of violet and blue light and thus the light delivered in the blue region is less compared to the single-peak blue lights. Since almost none of the violet light reaches the bottom of the specimen, radiant power delivered in this spectral region is effectively "wasted" at the bottom, but not near the top surface. This helps to explain why the radiant exposure delivered at the bottom of the Filtek Supreme Ultra specimens was 0.3 J/cm^2 when photoactivated with the broad-spectrum lights, while it was higher (0.4 J/cm^2) when the single-peak blue light was used. The radiant exposure delivered at the bottom of the translucent shade of Tetric EvoCeram specimens (1.1 J/cm^2 when photoactivated with the broad-spectrum lights), was also higher (1.2 J/cm^2) when the single-peak blue light was used. The ratio of blue and violet light transmitted appears to be affected by the composition of the material since there was a greater percentage of violet light transmitted through the Filtek Supreme Ultra A2 than through the other RBCs (Figure 5). This is likely due to the exclusive use of nanosized filler particles in Filtek Supreme Ultra that result in less light scattered in the 400 nm range when compared to the other RBCs that use larger sized filler particles. Of note, since twice as much light was transmitted through the Tetric EvoCeram T than through the Tetric EvoCeram A2, even though both were the same brand of RBC, the shade of the material influences the amount of both blue and violet light transmission. The increased amount of energy delivered at the bottom of Tetric EvoCeram T (Table 3 and Figure 4) may explain why there was no significant difference between degree of double-bond conversion when using the single-peak blue and the broad-spectrum lights for this translucent shade, while there was a significant difference between the degree of conversion using the same lights for the A2 shade of the same RBC (Table 2).

The reduced transmission of violet light at depth is a concern if violet light is required to activate some of the photoinitiators used in the RBC, since the biocompatibility of restorations is directly correlated with the degree of conversion of RBCs.[15] If the alternative initiators at the bottom of restorations, close to the pulp or to the gingival tissues, are not used up, there may be increased release of unwanted leachates from the RBC. The concern is that the RBC may appear to be adequately polymerized if sufficient blue light is delivered to activate the camphorquinone photoinitiator, but still may contain the unused alternative photoinitiators at the bottom.

The second null hypothesis was also rejected. Equivalent or higher microhardness and degree-of-conversion values were achieved at the bottom surface when 1200 mW/cm^2 was used compared to 3600 mW/cm^2. Not all RBCs responded in the same manner to the different irradiance levels. This may be related to the different composition among these four products, in that they likely have different polymerization kinetics. High-irradiance photoactivation could potentially cause a lower degree of conversion because there are more radicals being formed at the same time, which in turn leads to more biradical terminations.[10] Slower polymerization rates should produce fewer polymer growth centers, leading to a higher density of linear chains.[28,29] Also, using a high irradiance should produce polymers with higher cross-linked density than when using low irradiance because of the rapid formation of the polymeric chain. These differences would lead to different mechanical properties of the material, such as hardness, but without necessarily altering its degree of conversion.

It is important to note that the previous studies that analyzed polymerization kinetics used very low irradiances,[30] from 3.1 to 50 mW/cm^2, or very high irradiances[31] of up to 7500 mW/cm^2, while in the present study, the 'low' irradiance was close to 1200 mW/cm^2, and the higher irradiance was close to 3600 mW/cm^2 (Table 1). Thus, the low irradiance used in the present study should not be considered low, but instead is a representative standard irradiance value for contemporary curing lights. The high irradiance

levels used in this study are similar to several high-irradiance light curing units.

The third null hypothesis was rejected since the Pearson correlation showed a direct linear correlation between bottom microhardness and degree-of-conversion results (Figure 3). Previous studies have also reported positive correlations between microhardness and degree of conversion.[32,33] Since these two independent tests produced the same outcomes, there is more confidence in the conclusions of this study.

Considering the results of this study, for shallow cavities or thin increments, broad-spectrum lights should be used to photocure RBCs that use alternative photoinitiators in their composition. When restoring deeper cavities with a single increment of composite using a broad-spectrum light, the exposure time should be increased since little violet light penetrates down to 2.5 mm. The aim is to deliver the same radiant exposure to the bottom of the composite as would be delivered using a single peak light.

Regarding the use of high irradiance lights, this study supports previous reports [9-11] that high irradiance levels and short (five-second) exposure times offer no benefit when photoactivating RBC restorations. Lower irradiance and longer exposure times may produce RBCs with better physical properties and are preferable in clinical situations where small errors in the angle or the position of the tip of the LCU would have less of a negative effect on the total amount of energy delivered to the restoration. For example, if one second of exposure was lost during a five-second exposure of a RBC, this would represent a decrease of 20% of the total radiant exposure. If one second of exposure was lost during a 15-second exposure at the lower irradiance values, this would represent only a 7% decrease in the total radiant exposure to the RBC.

CONCLUSIONS

Considering the limitations of this study and the different behaviors of the tested materials, the emission spectra from the LCUs influenced the polymerization of the tested RBCs. The microhardness of the materials that used alternative photoinitiators in their composition was enhanced at the top surface with the use of broad-spectrum lights. However, this effect was lost at the bottom surface, where little violet light was observed. Also, different shades of the same brand allowed different amounts of light to reach the bottom of the RBC.

Even when the same radiant exposure was delivered, the irradiance levels influenced the polymerization of the tested RBCs. Equivalent or higher microhardness and degree-of-conversion values were achieved at the bottom surface when 1200 mW/cm^2 was used compared to 3600 mW/cm^2.

Acknowledgements

The authors wish to thank Ultradent for providing the custom made curing units for this study. They also thank the University of São Paulo, Santander Bank, and the Dalhousie Faculty of Dentistry Research Fund for supporting this study. The manufacturers kindly provided the resin-based composites for this study.

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.

(Accepted 18 January 2017)

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