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Effect of Thickness on Light Transmission and Vickers Hardness of Five Bulk-fill Resin-based Composites Using Polywave and Single-peak Light-emitting Diode Curing Lights

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Clinical Relevance

There is no evidence of a clear advantage for using a polywave light-curing unit over a single-peak light-curing unit when photopolymerizing bulk-fill resin-based composites that use a combination of camphorquinone and germanium-based photoinitiators.

SUMMARY

Objectives: This study compared light transmission through different thicknesses of bulk-fill resin-based composites (RBCs) using a polywave and a single-peak light-emitting diode light-curing unit (LCU). The effect on the surface hardness was also evaluated.

Methods: Five bulk-fill RBCs were tested. Specimens (n=5) of 1-, 2-, 4-, or 6-mm thickness were photopolymerized for 10 seconds from the top using a polywave (Bluephase Style) or single–peak (Elipar S10) LCU, while a spectrophotometer monitored in real time the transmitted irradiance and radiant exposure reaching the bottom of the specimen. After 24 hours of storage in distilled water at 37°C, the Vickers microhardness (VH) was measured at top and bottom. Results were analyzed using multiple-way analysis of variance, Tukey post hoc tests, and multivariate analysis (α=0.05).

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Results: The choice of LCU had no significant effect on the total amount of light transmitted through the five bulk-fill RBCs at each thickness. There was a significant decrease in the amount of light transmitted as the thickness increased for all RBCs tested with both LCUs (p<0.001). Effect of LCU on VH was minimal (η_p^2=0.010). The 1-, 2-, and 4-mm-thick specimens of SDR, X-tra Fill, and Filtek Bulk Restorative achieved a $VH_{bottom/top}$ ratio of approximately 80% when either LCU was used.

Conclusions: The total amount of light transmitted through the five bulk-fill RBCs was similar at the different thicknesses using either LCU. The polywave LCU used in this study did not enhance the polymerization of the tested bulk-fill RBCs when compared with the single-peak LCU.

INTRODUCTION

The use of resin-based composites (RBCs) for direct restorations has become routine in dental practice. The mechanical properties and abrasion resistance of RBCs continues to improve,[1] and they can offer an esthetic restoration for the patient. However, adequate polymerization is required to meet the manufacturer's specifications for the RBC that should, in turn, improve the long-term success of the RBC restoration. It is known that restorations that are poorly polymerized may fail prematurely because of the increased incidence of secondary caries, bond failure to the tooth, margin defects, or restoration fracture.[2,3] Additionally, the biocompatibility of the restoration is negatively affected if the RBC is inadequately polymerized.[4]

Contemporary RBCs use blue visible light to initiate the photopolymerization reactions. This technology is based on the use of photoreactive systems that absorb photons at specific wavelengths of light from the light-curing unit (LCU). The photoinitiator molecule forms free radicals that initiate the polymerization process by converting the carbon-carbon double bond in the methacrylate groups in the monomer into carbon-carbon single bonds, thus forming both longer polymer chains, and cross-linked chains. The success of this technology depends on matching the emission spectrum from the LCU to the wavelength-dependent photoabsorption of the photoinitiator present within the RBC and on the RBC receiving sufficient photons.[5]

This spectral matching was not a problem when quartz tungsten-halogen (QTH) units were used because these LCUs delivered a broad-emission spectrum of light ranging from ~375 to ~510 nm. However, light-emitting diodes (LEDs) have become the most commonly used light source in contemporary LCUs, and these LEDs emit a narrower range of wavelengths compared with QTH units.[6]

Most contemporary LED units use blue LED chips that produce a relatively narrow band of wavelengths, with a typical full width at half of the maximum wavelength peak of only ~25 nm. The emission spectrum from these units usually peaks in the 450-nm to 470-nm wavelength range and they deliver almost no light below 420 nm.[7] These blue LED units will efficiently cure resins that use camphorquinone (CQ), which is the most commonly used photoinitiator in RBCs.

However, the bright yellow color of CQ limits its use, particularly in very light or translucent shades of RBC.[8] Therefore, some RBCs and bonding systems include alternative photoinitiators that are not as chromogenic as CQ,[9] such as monoacylphosphine oxide and derivatives of dibenzoyl germanium, which are primarily activated by shorter wavelengths (below 420 nm) of violet light.[10] This requirement for shorter wavelengths has proven to be a problem for single-emission-band LED units that emit light mainly in the 450-nm to 470-nm wavelength range and has led to the introduction of a third generation of broad-spectrum multiple-peak LED violet/blue LCUs.[7,11-13] These broad-spectrum violet/blue LCUs use a combination of two or more different color LED chips to deliver light in both the 440-nm to 470-nm range and shorter wavelengths below 420 nm.[11,12] One manufacturer, Ivoclar Vivadent, has registered the term *polywave* to describe their broad-spectrum LED violet/blue LCU. Such broad-spectrum LED units have been reported to polymerize 2-mm thick specimens of some resins to a greater extent than single-emission-band LED blue curing units, even though both units were delivering similar irradiance values.[12]

Recently, bulk-fill RBCs have become popular to fill posterior teeth. While most early bulk-fills were flowable composites, high-viscosity bulk-fill RBCs are now available. These materials can be light cured in increments of 4 or 5 mm, instead of the customary 2-mm thickness.[14] The photoinitiator system used in most bulk-fill RBCs is still CQ based, as in the regular light-cured RBCs, although Tetric EvoCeram Bulk Fill includes additional initiators, such as Ivocerin. This germanium-based initiator system has a greater photo-curing activity than CQ and an absorption spectrum that extends from below

Table 1: *Materials, Manufacturers, and Chemical Composition of Matrix and Filler and Filler Content by Weight (w) and Volume (v)%*[a]

Material and Shade	Abbreviation	Manufacturer, Batch	Resin Matrix	Filler	Filler (w/v) %
TetricEvo Ceram Bulk Fill, IVA	Evo-Bulk	Ivoclar-Vivadent, V02758	Dimethacrylate	Ba-Glass, YbF3, mixoxide, PPF	79–81/60–61
SDR Posterior Bulk Fill Flowable U	SDR	Dentsply, 1603000897	Mod UDMA, EBPADMA, TEGDMA	Ba-Al-F-B-Si glass, Sr-F-Si glass	68/45
X-tra Fill, U	X-tra Fill	Voco, 1626156	Bis-GMA, UDMA, TEGDMA	Inorganic filler	86/70.1
Filtek Bulk Fill Flowable Restorative, A2	Filtek-Flo	3M-ESPE, N672461	UDMA, Procrylat, Bis-EMA, Bis-GMA	Zirconia/silica and ytterbium trifluoride	64.5/42.5
Filtek Bulk Fill Posterior Restorative, A2	Filtek-Bulk	3M-ESPE, N698655	AUDMA, UDMA and 1, 12-dodecane-DMA	Zirconia/silica and ytterbium trifluoride	76.5/58.4

Abbreviations: Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; Bis-GMA, bisphenol glycidyl dimethacrylate; EBPADMA, ethoxylated bisphenol-A-dimethacrylate; PPF, prepolymerized fillers; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.
[a] *Data were provided by the manufacturers (missing entries indicate where the data was unavailable). Other abbreviations according to periodic system of elements.*

380 nm up to 460 nm, with a peak absorption close to 408 nm.[15]

The polywave style of LED units should polymerize all types of RBC. However, due to the location of the LED emitters within the unit, the spectral irradiance may not be uniformly distributed across the light tip,[16,17] thus affecting the photocuring of some RBCs.[18] Furthermore; the lower wavelengths from these devices may be unable to penetrate the thicker specimens of bulk-fill RBCs in sufficient quantity to activate the photoinitiators at the bottom of the RBC.

The aim of this study was to quantify and compare the amount of light that was transmitted through different thicknesses of five bulk-fill RBCs using a polywave and a single-peak LED curing light, and to evaluate their effect on the Vickers microhardness at the bottom of the specimens. The tested null hypotheses were that 1) the same amount of light would be transmitted at each thickness through the five bulk-fill RBCs, 2) there would be no difference in the radiant exposure delivered in the 350-425 nm wavelength region from the polywave LCU at the bottom of the five brands of RBC, and 3) the hardness at the bottom of the specimens would be the same after using either of the two LCUs.

METHODS AND MATERIALS

The five bulk-fill materials used are reported in Table 1. For each material, four different thicknesses (1, 2, 4, and 6 mm) were tested. The specimens were prepared in white Delrin ring-shaped molds. The specimens were light cured by positioning the curing light tip at 0-mm distance, perpendicularly, and centered over the sample's surface. A mechanical arm was used to repeatedly and accurately position the LCU over the specimens. Two different commercial LCUs were used; one was a single peak light (Elipar S10, 3M, St Paul, MN, USA) that delivered, according to the manufacturer, an irradiance of 1200 mW/cm^2 in the wavelength range of 430-480 nm, and the other was a broad spectrum polywave light (Bluephase Style, Ivoclar Vivadent, Schaan, Liechtenstein) that delivered, according to the manufacturer, an irradiance of 1100 mW/cm^2 in the wavelength range of 385-515 nm. Both LCUs were used according to the manufacturer's recommended exposure time of 10 seconds. The light guide used was the original version supplied with the Bluephase Style LCU (the manufacturer has subsequently updated its light guide to provide a more homogenous light output, but this also decreased the radiant power output). Five specimens were made in each group.

A laboratory-grade USB4000 spectrophotometer (Ocean Optics, Dunedin, FL, USA) inside a MARC Resin Calibrator (BlueLight Analytics Inc, Halifax, NS, Canada) was used to measure, in real time, the transmitted irradiance that was emitted from the bottom of the specimens during light curing. The light was collected through a 4-mm-diameter cosine corrected detector (CC3, Ocean Optics). This detector is designed to collect all the radiation (light) arriving at 180°, thus eliminating some of the optical interface problems associated with the geometry of light collection. The MARC software quantified the total radiant exposure that reached the bottom of the specimens from both LCUs by integrating the area under the irradiance curves in the 350-425 nm and the 425-500 nm wavelength ranges. To protect the tip of the light guide and the sensor of the spectrometer, a 10-μm-thin transparent plastic foil covered the top and bottom of the specimens. This foil did not affect the transmitted wavelengths of light, but the two thicknesses combined reduced the irradiance reaching the detector by 10%.

To remove any oxygen inhibition layer, the cured specimens were lightly polished using copious water coolant and silicon carbide paper (grit size 1200 and 4000), and then stored in distilled water at 37°C for 24 hours. The specimens were blotted dry and Vickers microhardness (VH) was measured. A 200-g load was delivered by the Vickers indenter with a dwell time of 30 seconds using a microhardness tester (Matsuzawa Seiki Co, Ltd, Tokyo, Japan). Three indents were made no closer than 1 mm to the specimen margins and 1 mm distant from each other. They were averaged to yield a single mean microhardness (VH) value for the top and bottom surfaces of each specimen. A VH bottom/top ratio ($VH_{b/t}$) was also calculated.

Statistical Analysis

A statistical program SAS version 9.2 (SAS, Cary, NC, USA) was used to perform the analyses. Averages and standard errors of the means were calculated for the light irradiance, the radiant exposures at each increment thickness, and for each material. The normality of data was checked and confirmed before the results were compared between the two LCUs for each RBC at each increment thickness among the different incremental thicknesses, within each material, and among the 5 RBCs using multiple-way analysis of variance (ANOVA). Multiple-way ANOVA was also used to determine if there were significant differences in the VH at the bottom for the different RBCs at each increment thickness and each LCU. Tukey post hoc tests were used to assess the adjusted significant pair differences; α was set at 0.05. A multivariate analysis (general linear model, α=0.05) was used to assess the effect of the RBC, increment thickness, and LCU on the light irradiance, radiant exposure, and VH. For each increment thickness and RBC, the mean response and standard error of the mean were plotted for all dependent parameters (light irradiance, radiant exposure, and VH) using GraphPad Prism 5 (GraphPad Software, San Diego, CA, USA).

RESULTS

The mean values of the amount of transmitted light irradiance and the radiant exposure arriving at the bottom of each of the RBC specimens by each LCU are summarized in Table 2, together with the percentage of the light that arrived at the bottom of the specimens compared to what was delivered to the top surface. Multiple-way ANOVA revealed no significant difference in the total amount of light transmitted through the four different thicknesses when comparing the polywave LCU or the single-peak LCU: p=0.79, p=0.76, p=0.39, and p=0.45 for 1-, 2-, 4-, and 6-mm thicknesses respectively for irradiance; and p=0.25, p=0.27, p=0.99, and p=0.58 for the 1-, 2-, 4-, and 6-mm thicknesses, respectively, for the radiant exposure.

At each increment thickness, there was a significant difference in the amount of transmitted irradiance and total radiant exposure arriving at the bottom of the specimens among the five bulk-fill RBCs ($p<0.001$) for both LCUs (Figure 1). The amount of transmitted light irradiance and total radiant exposure were the highest in SDR and the lowest in Filtek Bulk Fill Flowable at all thicknesses and for both LCUs. Multivariate analysis showed that the radiant exposure and irradiance were significantly affected by the brand of RBC (0.698, 0.699) and by the thickness (0.965, 0.970), respectively.

Figure 2 shows graphs of the emission spectra through SDR (the most translucent RBC) and Filtek Bulk Fill Flowable (the least translucent) from both LCUs, and at each thickness. Figure 3 shows that the transmitted radiant exposure in the 350-425 nm wavelength range from the polywave LCU was less than one tenth of the light transmitted in the 425-500 nm wavelength range. In 10 s, less than 0.2 J/cm^2 of light in the 350 to 425 nm range was transmitted through 6 mm of any of the tested RBCs. The radiant exposure in the 350-425 nm wavelength range that reached the bottom of the specimens relative to what was delivered to the top was the lowest for EvoCeram Bulk Fill: 10%, 7.7%, 1.7%, and 0.0% at the 1, 2, 4, and 6 mm thicknesses, respectively.

There was a significant drop in the VH at the bottom as the increment thickness increased for both LCUs ($p<0.0001$). The decrease in the VH at the bottom and $VH_{b/t}$ ratio of the specimens with each increase in thickness followed the same pattern for both LCUs (Figure 4). The 1-, 2-, and 4-mm thickness of SDR, X-tra Fill, and Filtek Bulk Fill Posterior bulk-fill RBCs achieved a $VH_{b/t}$ ratio within one standard deviation of 80% when either LCU was used. At the 6-mm thickness, none of the tested RBCs achieved the 80% $VH_{b/t}$ value using either LCU.

Multivariate analysis showed that the brand of RBC had a significant effect (η_p^2=0.946) as well as

Table 2: *Mean Irradiance and Mean Radiant Exposure Among the Different Materials Through 1 to 6 mm of Each RBC and the Percentage (%) of What Reached the Bottom Relative to What Was Delivered to the Top (0 mm)*[a]

Increment Thickness	Bluephase Style					Elipar S10				
	Material	Irradiance		Radiant Exposure		Material	Irradiance		Radiant Exposure	
		Mean (SE)	%	Mean (SE)‘	%		Mean (SE)	%	Mean (SE)	%
0		1083		11.7			1196		12.5	
1	SDR	779.2^{a}(64.0)	72	8.3^{a}(0.7)	71	X-tra Fill	766.0^{a}(65.5)	64	7.8^{a}(0.7)	62
	Evo-Bulk	743.2^{a}(17.9)	69	8.0^{a}(0.2)	68	SDR	757.0^{a}(19.7)	63	7.7^{a}(0.3)	62
	X-tra Fill	716.2^{a}(24.7)	66	7.7^{a}(0.3)	66	Evo-Bulk	692.0^{a}(36.9)	58	7.2^{a}(0.4)	58
	Filtek-Bulk	$641.6^{a,b}$(12.2)	59	$7.0^{a,b}$(0.2)	60	Filtek-Bulk	688.8^{a}(14.6)	58	7.1^{a}(0.1)	57
	Filtek-Flo	544.8^{b}(25.3)	50	5.8^{b}(0.2)	50	Filtek-Flo	476.0^{b}(8.0)	40	4.8^{b}(0.1)	38
2	SDR	533.8^{a}(44.0)	49	6.0^{a}(0.5)	51	SDR	582.2^{a}(12.0)	49	5.9^{a}(0.1)	47
	X-tra Fill	$508.0^{a,b}$(19.6)	45	$5.5^{a,b}$(0.2)	47	X-tra Fill	500.4^{b}(17.3)	42	5.2^{b}(0.2)	42
	Evo-Bulk	$421.0^{b,c}$(10.7)	39	$4.5^{b,c}$(0.1)	39	Evo-Bulk	423.0^{c}(18.1)	35	4.2^{c}(0.1)	34
	Filtek-Bulk	$367.0^{c,d}$(10.3)	34	3.9^{c}(0.1)	33	Filtek-Bulk	363.6^{c}(5.6)	30	3.7^{c}(0.1)	30
	Filtek-Flo	323.0^{d}(8.8)	30	3.5^{c}(0.1)	30	Filtek-Flo	256.0^{d}(18.7)	21	2.6^{d}(0.2)	21
4	SDR	244.0^{a}(24.0)	23	3.1^{a}(0.6)	26	SDR	257.0^{a}(6.7)	21	2.7^{a}(0.1)	22
	X-tra Fill	162.2^{b}(9.0)	15	1.7^{b}(0.1)	15	X-tra Fill	174.0^{b}(7.0)	15	1.8^{b}(0.1)	14
	Evo-Bulk	$108.2^{b,c}$(6.9)	10	1.2^{b}(0.1)	10	Evo-Bulk	135.8^{c}(3.5)	11	1.4^{c}(0.0)	11
	Filtek-Bulk	107.4^{c}(9.5)	10	1.1^{b}(0.1)	10	Filtek-Bulk	131.2^{c}(6.5)	11	1.3^{c}(0.1)	10
	Filtek-Flo	89.8^{c}(3.2)	8	1.0^{b}(0.0)	8	Filtek-Flo	87.2^{d}(5.2)	7	0.8^{d}(0.1)	6
6	SDR	93.2^{a}(4.5)	9	1.0^{a}(0.1)	9	SDR	116.9^{a}(10.9)	10	1.2^{a}(0.1)	10
	X-tra Fill	62.2^{b}(6.5)	6	0.7^{b}(0.1)	6	X-tra Fill	67.4^{b}(4.1)	6	0.7^{b}(0.0)	6
	Filtek-Bulk	40.2^{c}(3.3)	4	0.4^{c}(0.0)	3	Evo-Bulk	42.2^{c}(0.1)	4	0.4^{c}(0.0)	3
	Evo-Bulk	37.4^{c}(3.3)	3	0.4^{c}(0.0)	3	Filtek-Bulk	39.8^{c}(1.6)	3	0.4^{d}(0.0)	3
	Filtek-Flo	30.4^{c}(2.5)	3	0.3^{c}(0.0)	3	Filtek-Flo	29.2^{c}(2.0)	2	0.4^{c}(0.0)	3

[a] *Mean irradiance (mW/cm^2) and radiant exposure (J/cm^2) are reported together with the standard errors of the means. Means with the same letter among the same increment thickness and light-curing unit are not significantly different. (Tukey honestly significant difference test, α=0.05).*

the increment thickness (0.881), but there was only minimal effect of the LCU (0.010) on the VH values.

DISCUSSION

Table 2 shows that the Elipar S10 delivered a slightly greater radiant exposure (12.5 J/cm^2) in 10 seconds compared with the Bluephase Style (11.7 J/cm^2). However, after passing through 1 to 6 mm of RBC, the irradiance and total radiant exposure delivered in the 350-500 nm wavelength range from the polywave and the Elipar S10 LED LCUs were similar for each RBC, but different among the five RBCs. Therefore, the first null hypothesis was accepted and proved the assumption that differences in light transmission appear to be more dependent on RBC material and thickness, rather than on the LCU, provided that similar radiant exposures are delivered.[19,20]

The second null hypothesis that there would be no difference in the radiant exposure delivered in the 350-425 nm wavelength region from the polywave LCU at the bottom of the five brands of RBC was rejected. Figures 2 and 3 show that as the increment thickness increased, the radiant exposure in the 350-425 nm wavelength range that arrived at the bottom from the Bluephase Style was significantly decreased. Figure 3 shows that the light transmitted through 1 mm of RBC in the 350-425 nm wavelength range was less than one tenth of the light transmitted in the 425-500 nm wavelength range and became minimal in comparison to the radiant exposure delivered in the 425-500 nm wavelength range as the increment thickness increased. The Tetric EvoCeram Bulk Fill RBC transmitted the least amount of energy in the 350-425 nm wavelength range. In the 350-425 nm range, only 1.7% of what was delivered to the top reached the bottom of the specimens, and nothing could be detected (0%) at the bottom of the 6-mm-thick specimens. This raises questions about the need to include the lower short wavelengths in LED curing lights used to cure bulk-fill RBCs and supports the findings of a 2017 publication by Sampaio and others[16] that the amount of violet light was insufficient to cure the RBC at greater depths. They found that overall

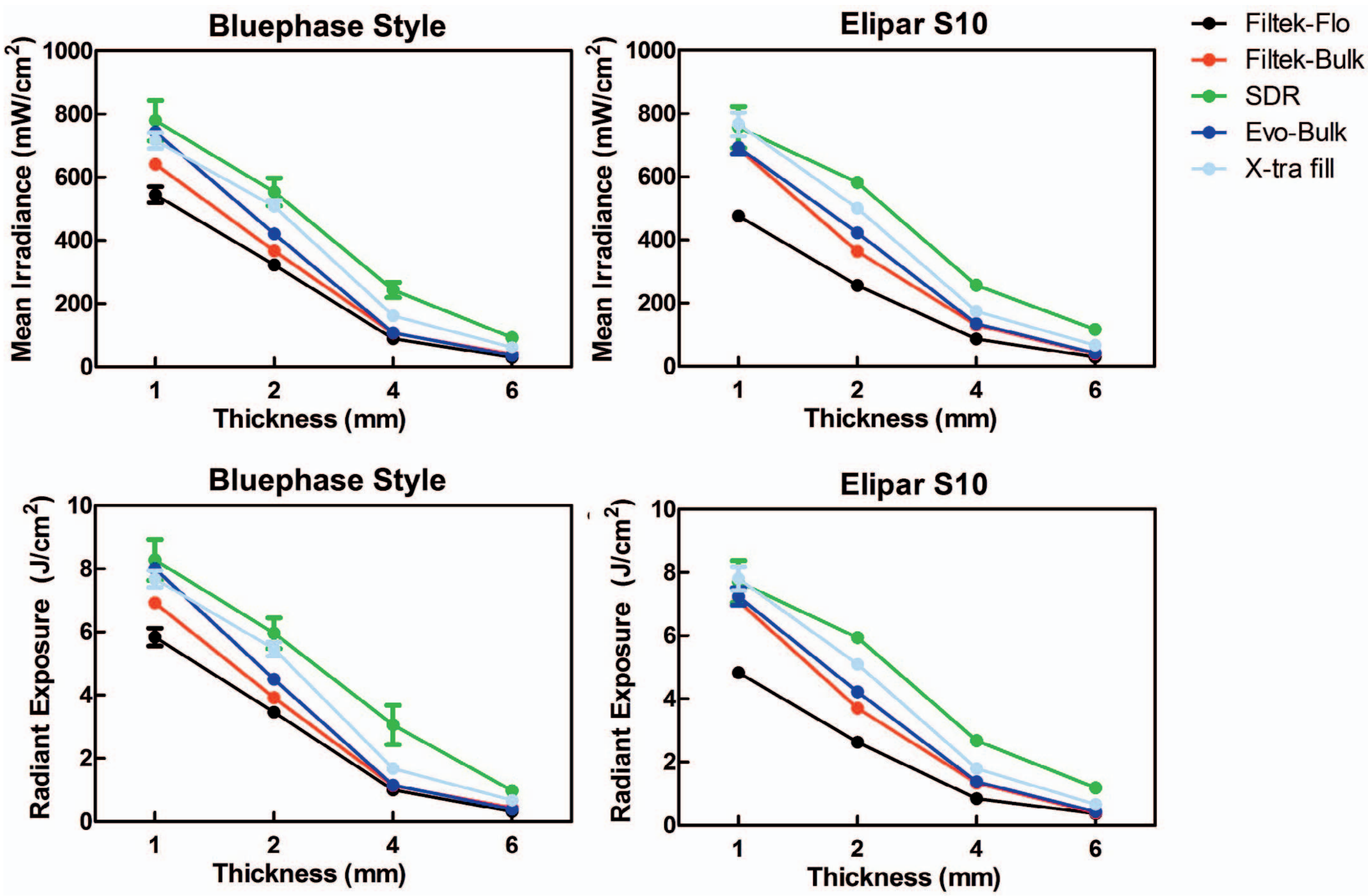

Figure 1. *Irradiance and radiant exposure transmitted to the bottom surfaces of the specimens at the different thicknesses from both LCUs. There was a significant decrease in the transmitted irradiance and radiant exposure as thickness increased in all RBCs tested with both LCUs* ($p<0.001$).

light-curing was the worst in the deeper regions that were exposed mostly to violet light, and this translated into lower degree of conversion values in this region.[16] Other studies have also found that increasing the RBC thickness had a greater negative effect on transmission of violet light (350-425 nm) than on blue light (425-550 nm).[21,22]

The increased absorption of violet light compared with the longer wavelength blue light may be related to the relationship between the wavelength of the light from the LCU and the dimensions of the filler particles used within the RBC. According to the Rayleigh effect, the filler particles within the RBC will be more likely to scatter shorter wavelengths of light.[10] This effect will be more pronounced at the shorter wavelengths (below 425 nm) delivered by the polywave LED LCU compared with the longer wavelength (at 460 nm) delivered by both LED LCUs.[23]

Another explanation for the reduced effectiveness of the polywave LCU as the RBC thickness increases may be the differences in the absorption of CQ and the alternative photoinitiators used within the RBC. A study that used a phenanthrenequinone (PQ) initiator reported that its peak absorption was at 413 nm, and it had eight times the absorbance of CQ; However, even when 1200 mW/cm^2 was delivered for 40 s to an RBC that used the highly reactive PQ initiator, the depth of cure was less (2.7 mm) compared with similar CQ-based RBCs (4.2 mm). It was suggested that due to the high absorbance of PQ, most of the light photons were depleted in the top layers of the RBC and never reached the bottom of the RBCs.[24] Ivocerin has higher absorbance than CQ and therefore, may also absorb most of the violet light in the first one or two millimeters of the RBC, thus preventing the lower wavelengths from reaching deeper into the RBC.

The photoinitiator content of RBC materials is not always disclosed and varies greatly among different brands of similar shades, or even among different shades within the same product brand.[25] Thus, the manufacturers of broad-spectrum polywave LCUs

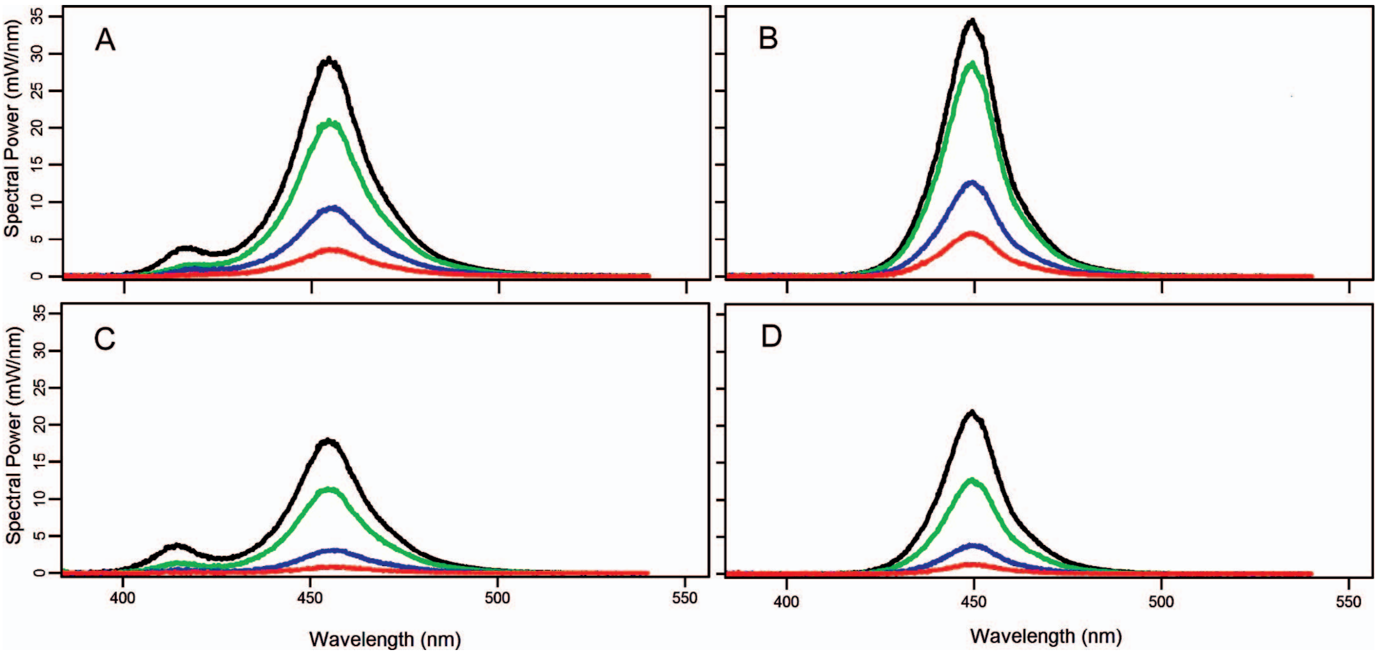

Figure 2. *Effect of specimen thickness on the emission spectrum transmitted to the bottom surfaces of the specimens from (A) Bluephase Style with SDR, (B) Elipar S10 with SDR, (C) Bluephase Style with Filtek Bulk Fill Flowable, and (D) Elipar S10 with Filtek Bulk Fill Flowable at 1 mm (black), 2 mm (green), 4 mm (blue), and 6 mm (red) thick RBC.*

(e.g., Ivoclar Vivadent, GC, Ultradent, and Kulzer) claim that because their units produce a broad emission spectrum compared with other single-peak LED-based units, they can photo-cure all current RBCs, no matter what photoinitiator is used.[23,26]

According to the manufacturer, the Elipar S10 LED LCU delivers an emission spectrum of 430-480 nm with a single peak emission at 455±10 nm. This LCU was chosen because it can efficiently cure RBCs that contain CQ, which is the most commonly used photoinitiator in RBCs. However, the Elipar S10 was also found to be effective at photo-curing EvoCeram Bulk Fill, even though this LCU delivers very little light below 430 nm. This may be attributed to the use of Ivocerin in EvoCeram Bulk Fill. Although Ivocerin has a peak absorbance close to 408 nm, it is sensitive to light up to 460 nm, and nearly 50% of its peak absorbance occurs at 440 nm.[27] The overlap in the absorbance of Ivocerin and the emission spectrum from the Elipar S10 allowed the initiation of the Ivocerin by the Elipar S10 LCU. The Bluephase Style LED LCU was chosen because it uses three LED emitters: one violet and two blue, with spectral emissions peaking near 410 nm (violet) and 457 nm (blue) and it is known to be a polywave broad-spectrum violet/blue LCU.

There was a significant difference in the amount of light that was transmitted among the five bulk-fill

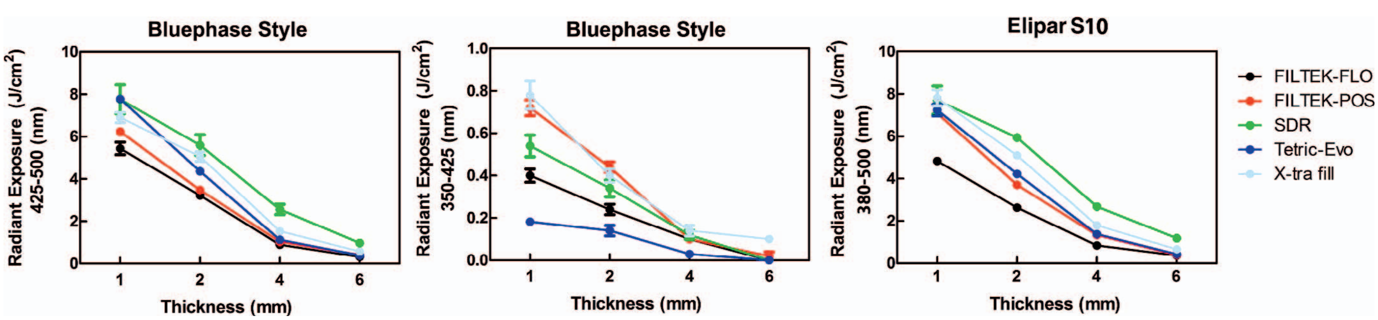

Figure 3. *Radiant exposure transmitted to the bottom surfaces of the specimens delivered in the 350-425 and 425-500 nm wavelength ranges to the bulk-fill RBCs at different thicknesses from the Bluephase Style and in the 380-500 nm range from the Elipar S10. Note the different radiant exposure scale in the 350-425 nm range and how very little violet light passed through 4 mm of RBC. There was a significant decrease in the transmitted radiant exposure as thickness increased in all RBCs tested with both LCUs ($p < 0.001$).*

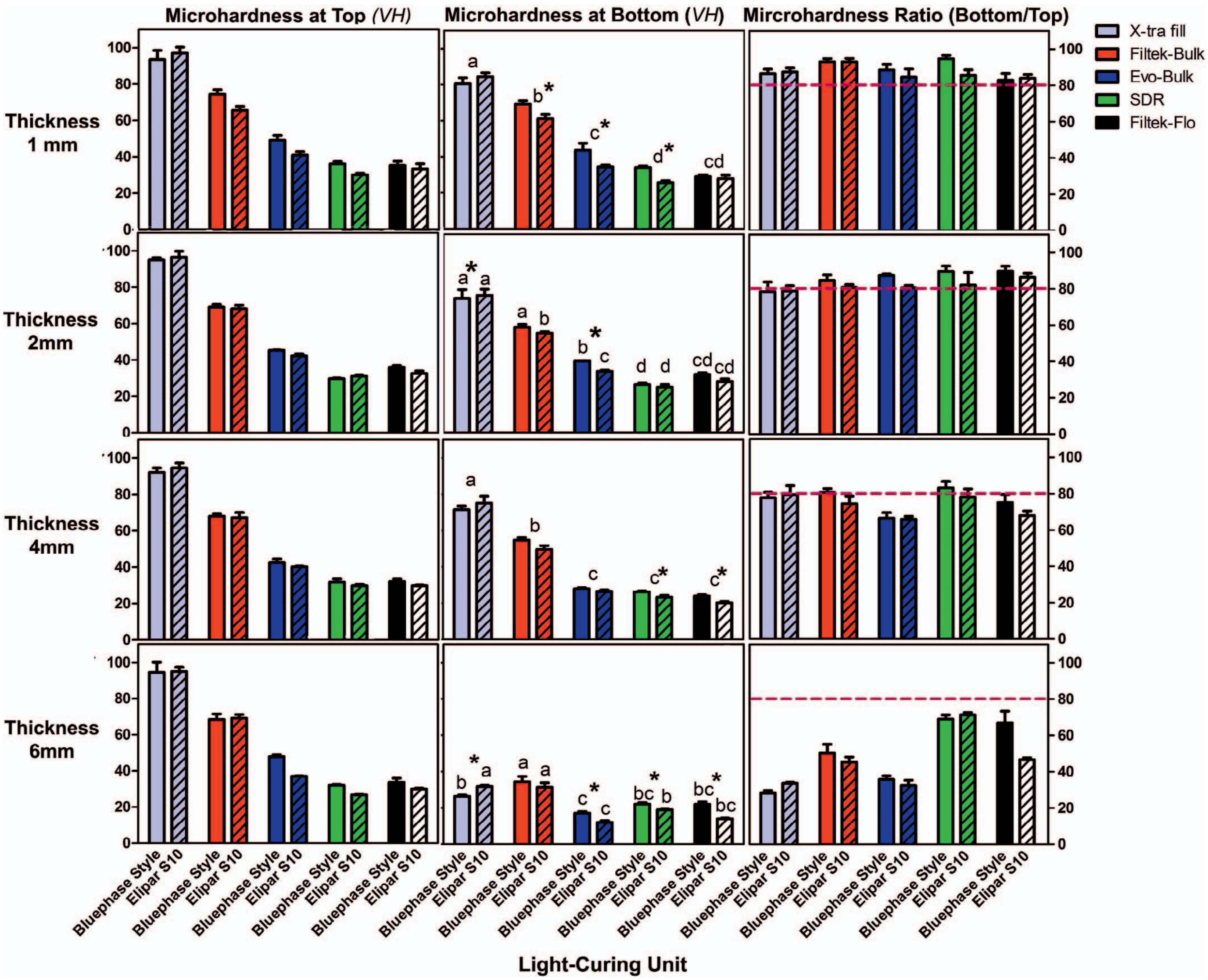

Figure 4. *Vickers microhardness (VH) values at the top, at the bottom and the bottom to top ratio ($VH_{b/t}$) of each bulk-fill RBC at the different increment thicknesses using both LCUs. Vertical lines represent the standard errors of the means. Letters represent significant differences between the bulk-fill RBCs at same thickness. Asterisks represent significant differences within the same bulk-fill RBC at the same thickness between the two LCUs ($p<0.05$). The horizontal dotted line represents the 80% $VH_{b/t}$ ratio.*

RBCs ($p<0.0001$). The high translucency of X-tra Fill relative to the other RBCs, even with high filler amount, may be related to the larger filler particle size and because the manufacturer has matched the refractive indices of the filler particles and the resin matrix.[28] This improves the light transmission through the RBC.[29] The decreased filler content in SDR and the presence of a special photoactive group in this RBC may have enhanced its light transmitting properties. The lower translucency of Filtek Bulk Fill Flowable may be related to the addition of small particle zirconia fillers into this RBC. Due to its high refractive index, zirconia has been reported to reduce light transmission through some experimental materials. However; this partial substitution of particulate glass fillers with zirconia/silica fillers (2.5 and 5.0 wt%) should improve the mechanical properties, such as flexural strength and fracture toughness of the RBC.[30] Thus, when formulating an RBC, it is a compromise between achieving adequate light transmission and obtaining the optimum physical properties for the RBC.

Since both LCUs delivered a similar radiant exposure, the depth of cure was only minimally influenced by the LCU used; consequently, the third null hypothesis was partially accepted. The decrease in the hardness at the bottom of the specimens with each increase in thickness followed the same pattern for both LCUs. This is in agreement with a study by Menees and others,[31] who found that the effect of the LCU type on the depth of cure was not significant when two bulk-fill RBCs were irradiated with either a polywave or a single-peak LED LCU. This may be because the percentage of reduction in the total radiant exposures transmitted to the bottom of the specimens relative to what arrived at the top was similar in the two LCUs (Table 2). With decreasing light penetration and increasing distance from the irradiated surface, a decrease in the degree of conversion and hence a decrease in the hardness values would be expected.[32]

It has been previously reported that the emission spectrum across the light tip of the polywave Bluephase Style with the original nonhomogenizer light guide was not uniform.[33] This resulted in nonuniform nanohardness across the top and bottom surfaces; the nano hardness within the bulk of the specimens was also not uniform.[34] In a previous study that investigated 1.2 mm thick conventional RBCs that did not contain Ivocerin, increasing exposure duration beyond manufacturers' recommended times reduced the effects of beam inhomogeneity on surface and subsurface microhardness, especially for RBCs that contained both CQ and 2,4,6-trimethylbenzoyldiphenylphosphine oxide (Lucirin TPO) as the photoinitiators.[35] The hardness of RBCs has been used as an indirect method to assess the depth of cure[36] with a bottom to top hardness ratio ($VH_{b/t}$) of 80% is often used as a minimally acceptable hardness threshold value.[37] The use of a 10-second exposure time in this study may explain why not all the RBCs reached the 80% $VH_{b/t}$ value at the 4-mm thickness and suggests that longer exposure times may be required.

Menees and others[31] reported differences in the depth of cure when a metal mold was used compared with a tooth mold. They also reported greater deviation in the data when using a tooth mold and suggested that stainless steel molds are preferred.[31] White semitransparent Delrin molds instead of metal molds were used to prepare the samples in this study. Although these semitransparent molds are not what is specified by the ISO standard 4049 depth-of-cure test,[38] they may represent what occurs in the tooth more accurately instead of the completely opaque metal molds that are used in the ISO test. The white Delrin also offers consistent optical properties compared with using a tooth. However, despite using these semitransparent white molds, not all bulk-fill materials reached the 80% $VH_{b/t}$ value at the 4-mm depth when using the 10 s exposure time.

At the 6-mm thickness, none of the tested materials achieved the 80% $VH_{b/t}$ value using either LCU; thus, dentists may still need to use bulk-fill RBCs in two or more increments in deep cavities and should not attempt to light cure a 6-mm increment. This may be related to the drastic decrease in irradiance and radiant exposure that arrives at the bottom relative to what arrives at the top as the thickness increased for all five RBCS (Table 2 and Figures 1 through 3). The EvoCeram Bulk Fill had the lowest depth of cure and the most drastic decrease in the $VH_{b/t}$ ratio values, especially as the thickness increased. This observation is similar to findings of other studies,[32,39] Furthermore, this supports the observation that the depth of cure of CQ-based materials can be greater than that of TPO-based materials,[40] and the additional photoinitiator (Ivocerin) in EvoCeram Bulk Fill is not able to fully compensate for the lower translucency of this product. At 4 mm, SDR transmitted the greatest amount of light (3 J/cm^2) of all the tested RBCs and it showed the lowest drop in the $VH_{b/t}$ value for both LCUs (Table 2 and Figure 4). Of note, clinical studies have reported good successes for SDR when it was capped with a conventional composite in 5-year randomized controlled studies.[41,42] It was also reported that provided at least 3.23 J/cm^2 was delivered to SDR, changes in the radiant exposure had only a small impact on the degree of conversion and the depth of cure of this RBC.[20] A similar result was reported for Filtek Bulk Fill Flowable (3M) which required only 5.30 J/cm^2 to achieve a 4 mm depth of cure.[20] Table 2 shows that only ~1 J/cm^2 was transmitted at 4 mm, which may be why it did not achieve an 80% $VH_{b/t}$ ratio after 10 seconds of light exposure.

A reduced decrease in the degree of conversion as the incremental thickness increased has been reported when monomers of a higher molecular weight are used.[43] The SDR Posterior Bulk Fill Flowable that was used in this study included a high molecular weight urethane-based methacrylate resin polymerization modulator to delay gelation and reduce polymerization shrinkage without affecting the degree of conversion.[44] This may have increased the depth of cure. The same technology in used in SDR flow + Bulk Fill Flowable that has improved mechanical strength, wear resistance, and radiopacity.[45] Optimizing the resin components may also explain why the bulk-fill RBCs SDR, X-tra Fill, and Filtek Bulk Fill Posterior achieved a $VH_{b/t}$ ratio that was within one standard deviation of 80%. These materials contain urethane dimethacrylate (UDMA), and the copolymerization of bisphenol A-glycidyl methacrylate (bis-GMA) with UDMA or triethylene glycol dimethacrylate (TEGDMA) increases the conversion and creates a highly cross-linked, dense and stiff polymer network.[46]

The results show that the polywave broad-spectrum violet/blue LED LCU used in this study did not enhance the polymerization of the bulk-fill RBCs tested compared with the single-peak LED LCU, provided that similar radiant exposures were delivered. The effect of other polywave LED units on additional bulk-fill RBCs, particularly different shades and those that contain the alternative photoinitiators in addition to CQ, together with extended exposure durations, should be addressed in future studies using experimental resins of known formulations.

CONCLUSIONS

Within the limitations of the current study that used five commercial RBCs, the following conclusions may be made:

1. When similar radiant exposures were delivered, multiple-way ANOVA revealed no significant difference in the total amount of light transmitted through the four different thicknesses when comparing the polywave LCU or the single-peak LCU
2. After passing through 1 mm of RBC, the transmitted light in the 350-425 nm wavelength range was less than one tenth of the light transmitted in the 425-500 nm wavelength range and became minimal as the increment thickness increased.
3. Twenty-four hours after light curing and after polishing the RBCs, the 1-, 2-, and 4-mm thickness of SDR, X-tra Fill, and Filtek Bulk Fill Posterior bulk-fill RBCs achieved a $VH_{b/t}$ ratio that was within one standard deviation of 80% when either LCU was used.
4. When similar radiant exposures were delivered, the polywave broad-spectrum violet/blue used in this study did not enhance polymerization of the tested bulk-fill RBCs compared with the single-peak LCU.

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Conflict of Interest

The authors of this manuscript 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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