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The Effect of Irradiation Distance on Light Transmittance and Vickers Hardness Ratio of Two Bulk-fill Resin-based Composites

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ABSTRACT

The aims of this study were to assess the light energy transmission and Vickers hardness (VH) ratio of two bulk-fill resin-based composites (RBCs) (Tetric EvoCeram and Filtek) cured at different distances between the light curing unit's (LCU) tip and the surface of the restoration (T-S) using either a Bluephase G2, Bluephase® 'turbo tip' or Bluephase Style LCU. Samples were cured from the top at T-S distances of 2mm, 6mm and 10mm for 20 seconds. A MARC-Resin-Calibrator™ recorded the transmitted irradiance reaching the bottom of the sample, in real time. The VH was measured at the top and bottom after 24h of dark storage. Both the total light energy (TLE) transmitted through the samples and their VH ratios were reduced with increasing T-S distance. At 10mm T-S distance, the VH ratio values of samples cured with Bluephase G2 LCU were significantly greater than the samples cured with the other LCUs while the samples cured with Bluephase® 'turbo tip' showed the lowest values. It can be concluded that TLE transmitted through bulk-fill RBCs and their VH ratio reduces with increasing T-S distance but the rate of decline is LCU dependent. Bluephase G2 was associated with the smallest light attenuation.

INTRODUCTION

The polymerization of the resin-based composites (RBCs) occurs through a series of photochemical reactions resulting in a polymer being formed from monomers. In light-cured RBCs, the polymerization is initiated by photo-initiator(s), which are in turn activated by exposure to light energy from a light curing unit (LCU). One of the problems associated with light-cured RBCs is the limitation in the depth of cure.[1, 2] When the cavity is large, an incremental layering technique is considered to be the gold standard for the placement of RBC restorations,[1, 2] in approximately 2 mm thick increments to achieve adequate polymerization and to reduce polymerization shrinkage. However, the incremental layering technique is time consuming. Recently, several new restorative materials have been marketed as "bulk-fill" RBCs. The manufacturers claim that bulk-fill RBCs can be applied in layers of 4 mm to 5 mm without necessitating a prolonged curing time, associated with a time consuming layering process. To increase the depth of cure, manufacturers have used different strategies.[3] One way to enhance the depth of cure is to increase the translucency of the bulk-fill

RBCs, thus allowing more light energy transmission through the material.[4] This can be achieved by reducing the amount of filler (Filtek bulk-fill, Venus bulk-fill) or increasing the filler size (SDR, SonicFill, x-tra base, x-tra fil). This reduces the specific surface area between fillers and organic matrix and reduces light scattering.[3] The passing light is scattered at the filler-matrix interface due to differences in the refractive indices, appropriately matched refractive index of filler and organic matrix can maximize translucency and increase light transmission.[5] If the difference in refractive index between filler and organic matrix is large, then even at low filler loading, materials would be opaque.[5] Filtek bulk-fill RBC has been formulated to be more translucent for blue light by reducing the filler amount. This material contains additional zirconia fillers. A partial substitution of particulate glass fillers with zirconia/silica fillers (2.5 and 5.0 wt%) is found to enhance mechanical properties.[6] The manufacturer of Tetric EvoCeram bulk-fill has used a different strategy to enhance the depth of cure. They have added a patented photo-initiator, Ivocerin, in addition to the originally used photo-initiator(s) to act as a polymerization booster.[7] This recently introduced photo-initiator is a dibenzoyl germanium compound and it has higher photocuring activity than Camphorquinone (CQ) which leads to an enhanced degree of conversion in deeper layers of the material.[7] Moreover, the near-round shape of Tetric bulk-fill fillers have been shown to positively influence the translucency.[8]

Bulk-fill RBCs can be classified in two categories, flowable and higher viscosity paste versions. The flowable bulk-fill RBCs require an additional 2mm capping layer with conventional RBC. The use of flowable RBCs is said to reduce tooth sensitivity due to its wetting ability and its better adaptation to cavity walls, leading to less voids at the interface of the restoration and tooth structure.[9, 10] The advantage of viscous bulk-fill RBCs is their higher mechanical properties compared to flowable bulk-fill RBCs.[3] However, there is a concern when using these bulk-fill RBCs at high occlusal load as they have shown lower mechanical properties compared to highly filled nano-hybrid RBCs.[11]

The clinical success of any RBC restoration is directly related to the degree of polymerization.[12, 13] However, there are many variables that influence the amount of light energy delivered to the top and bottom surfaces of the restoration which may result in inadequate polymerization.[14] One of these variables is the distance between the tip of the LCU and the surface of the restoration (T-S). This factor is difficult to control as it depends on cavity size, tooth position in the arch and operator efficiency. Previous studies showed significant reduction in degree of polymerization at the bottom surface of RBC samples when the T-S distance increased.[15-17] However, the relationship between T-S distance, light energy delivery and degree of polymerization of RBC may not be similar for all LCUs as it may also depend on individual characteristics of the LCU e.g. LCU's tip geometry, lamp output intensity and tip optical properties.[14, 18] Several years ago a specific shape of LCU tip called 'turbo' tips were introduced. These tips are characterized by having an exit diameter smaller than the entry diameter. The light beam emitted by the lamp is therefore concentrated through a smaller area, thus increasing the amount of photons per unit area. This higher amount of energy emission is valid in the first millimeters but it will be less efficient than a standard tip at a larger distance from the RBC material.[19-22]

There are various methods to assess the extent of polymerization. One of these methods is surface Vickers hardness (VH) measurements. It has been reported that a bottom to top relative surface hardness ratio ≥ 80% is one which is indicative of a sufficiently cured RBC.[23-26]

The present study aims to assess the light energy transmission through bulk-fill RBCs when they are cured at different T-S distances by different LCUs and to measure the VH ratio.

The null hypotheses are as follows:

a. There is no significant difference in total light energy (TLE) transmitted through the bottom surface of the two bulk-fill RBC materials when cured at different T-S distances with different LCUs.

b. There is no significant difference in VH bottom/top ratio of the two bulk-fill RBC materials when cured at different T-S distances with different LCUs.

MATERIALS AND METHODS

The study was conducted using two bulk-fill RBCs, one viscous (Tetric EvoCeram bulk-fill, Ivoclar Vivadent AG, Schaan, Liechtenstein) and one flowable (Filtek bulk-fill, 3M™ ESPE™, U.S.A). The characteristics of the included bulk-fill RBCs are shown in Table 1. Three LCUs were included in this study, Bluephase® with turbo tip, Bluephase G2 and Bluephase Style with its original tip that lacked the homogenizer (Ivoclar Vivadent AG, Schaan, Liechtenstein). Five samples (n=5) were prepared for each material.

The MARC-Resin Calibrator™ (MARC-RC™) was used to measure the light irradiance delivered and transmitted through the RBC samples by each LCU, at each T-S distance. The MARC-RC™ system contains a NIST-referenced miniature spectrometer with a 3,648-element linear CCD array detector. MARC-RC™ has two sensors, the first one for measuring the irradiance delivered to the top surface of the samples (sensor 1) and the second one for measuring the irradiance transmitted through samples' bottom surface (sensor 2). Both sensors are CC3 cosine correctors (diameter 3.9 mm) designed to collect radiation (light) at around 180°. MARC™ custom software recorded the light irradiance (mW/cm^2) delivered to the sensor.

To measure the LCU's tip irradiance (i.e. the irradiance at zero distance) and the irradiance (mW/cm^2) delivered to the samples by each LCU at each T-S distance, a Mylar strip was placed first over sensor 1 then the LCUs were each individually mounted on a MARC-RC™ and centered perpendicularly over sensor 1. The delivered irradiance from each LCU was

Table 1. The characteristics of the bulk-fill RBC materials used in the study

RBC type	shade	Matrix	Filler	Filler content (w/v)	Photo-initiator	Recommended curing time (by manufacturer)
Filtek BF (flowable)	A2	Bis-GMA, UDMA, Bis-EMA(6), procrylat resins	Ytterbium trifluoride (YbF^3), zirconia, silica	64.5/42.5	Unstated	For shade A2 at increment depth of 4mm: • 40 seconds with all halogen or LED lights (with output 550-1000 mW/cm^2 in the 400-500 nm range) • 20 seconds with Elipar™ S10 LCU with output 1000-2000 mW/cm^2. (hold the light guide tip as close to the restorative as possible during light exposure)
Tetric EvoCeram BF(viscous)	IVA	Dimetha-crylate	Ba-Glass, YbF_3, mixoides, PPF	79-81/60-61	CQ, Ivocerin	• 20 seconds if light irradiance ≥ 500 mW/cm^2 • 10 seconds if light irradiance ≥ 1000 mW/cm^2

BF bulk-fill, Bis-GMA bisphenolglycidyldimethacrylate, UDMA urethanedimethacrylate, PPF pre-polymerized fillers

measured at 0 mm, 2 mm, 6 mm and 10 mm T-S distances. At each T-S distance, all LCUs were activated for 20 seconds.

For each material, samples were prepared in white Delrin® rings (5 mm in diameter and 4 mm in height). The 4 mm thick Delrin® ring was positioned on a Mylar strip, which in turn was placed on glass slide. For Tetric bulk-fill material, a single increment was gently condensed into the ring with a clean, dry flat plastic instrument ensuring the ring was filled completely and the excess material was removed from the ring with a flat plastic instrument. Another Mylar strip was placed on the top surface followed by a gentle manual pressure. Then the sample was placed on sensor 2.

For Filtek bulk-fill material, a Mylar strip was placed on sensor 2 to protect it and facilitate the removal of flowable material. Then the Delrin® ring was placed on it and the flowable Filtek bulk-fill material was injected from its syringe to fill the space inside the ring. For this flowable material, the samples were slightly overfilled to avoid producing a meniscus effect. Then the top surface was covered with another Mylar strip. The samples (n=5) were cured at different T-S distances (2 mm, 6 mm, 10 mm) for 20 seconds with the three different LCUs. At each T-S distance the LCU's tip was perpendicular to and centered on the sample's top surface by using the MARC-RC™ mechanical arm.

While the samples were cured, MARC-RC™ measured the irradiance at the bottom of the samples in mW/cm^2 and MARC-RC™ software converted this to J/cm^2 i.e. the amount of total light energy (TLE). After curing, the Mylar strips were removed and then all the samples were stored in identifiable paper envelopes in a dark room at 21.9±2°C and 53±3% humidity for 24 hours.

After 24 hours, the Vickers hardness number (VHN) was measured with a Micro Vickers Hardness Testing Machine (HM-200 Series). The indentation force was 300g for 10 seconds. Three measurements were recorded from near the center of both the top and bottom surfaces of each sample. For each sample, the three hardness values for each surface were averaged and reported as a single value. The mean VHN and hardness ratio of the samples were calculated and tabulated using the formula: Hardness ratio= VHN of bottom surface/ maximum VHN achieved at top surface X 100.

Results were compared using multivariate analyses (general linear model) and pairwise comparisons with Tukey method (α=0.05) by Minitab 17. The multivariate analyses assessed the effect of the parameters T-S distance (2, 6 and 10 mm), LCU (Bluephase G2, Bluephase® turbo tip and Bluephase Style) and material (Tetric EvoCeram and Filtek bulk-fill RBCs) on the VH ratio and light energy transmission. The normal (Gaussian) distribution and equal variance of the data were confirmed using the residual plots function by Minitab 17. The pairwise comparisons were performed within significant interactions using Tukey method to decrease the risk of type I error when making multiple comparisons. The results were presented as confidence intervals (CIs) and p-values and all the statistical comparisons were made at the 95% significance level.

RESULTS

LIGHT ENERGY TRANSMISSION

Figure 1 was obtained using MARC-RC™ software and it shows the emission spectra for the three LCUs at the different T-S distances. Table 2 shows the tip irradiance (i.e. the irradiance at zero distance), irradiance (mW/cm^2) and TLE (J/cm^2) delivered to the top surface of Filtek and Tetric bulk-fill RBC samples at the three distances with the three LCUs. The spectral peak (nm) and the amount of blue and violet lights (J/cm^2) emitted by each LCU at each T-S distance are shown in Table 3 while Table 4 shows the amount of blue and violet lights (J/cm^2) transmitted through the samples of both materials at 2 mm T-S distance with each LCU.

Table 2. The tip irradiance (mW/cm^2), irradiance (mW/cm^2) and TLE (J/cm^2) delivered to the samples by each LCU at each distance

LCU	Tip irradiance (mW/cm^2)	At 2 mm		At 6 mm		At 10 mm	
		Irradiance (mW/cm^2)	TLE (J/cm^2)	Irradiance (mW/cm^2)	TLE (J/cm^2)	Irradiance (mW/cm^2)	TLE (J/cm^2)
Bluephase G2	1191(6.7)	1247(19)	25.2(0.39)	1330.4(48.6)	26.85(0.96)	840.2(14.63)	16.96(0.29)
Bluephase® (turbo tip)	1763.2(6.6)	1466.4(5.27)	30.17(0.09)	624.8(2.25)	12.84(0.06)	271.6(0.84)	5.57(0.02)
Bluephase Style	1255.2(5.5)	1176.6(51.1)	24.54(1.08)	935.8(17.18)	19.51(0.35)	452.6 (4.03)	9.43 (0.09)

The values are expressed as mean (standard deviation).

Table 3. The peak wavelengths (nm) and the TLE (J/cm2) emitted by each diode at each T-S distance.

LCU	Peak wavelengths (nm)	At 2mm		At 6mm		At 10mm	
		Blue light	Violet light	Blue light	Violet light	Blue light	Violet light
		TLE (J/cm2)	TLE (J/cm2)	TLE (J/cm2)	TLE (J/cm2)	TLE (J/cm2)	TLE (J/cm2)
Bluephase G2	410 and 460 (0.2)	20.7 (0.3)	4.5 (0.1)	23 (0.4)	3.8 (0.7)	14.7 (0.1)	2.3 (0.1)
		82.1%	17.9%	85.8%	14.2%	86.5%	13.5%
Bluephase® (turbo tip)	456.6 (0.4)	29.9 (0.1)	0.2 (0.03)	12.7(0.04)	0.1 (0.03)	5.4 (0.01)	0.1 (0.03)
		99.3%	0.7%	99.2%	0.8%	98.2%	1.8%
Bluephase Style	408 and 457.2 (0.3)	19.5 (0.7)	5.1 (0.1)	15.9 (0.3)	3.6 (0.1)	7.9 (0.2)	1.5 (0.02)
		79.3%	20.7%	80%	18.5%	84%	16%

The values are expressed as mean (standard deviation)

Table 4 - The amount of blue and violet light (J/cm^2) transmitted through each material with each LCU at 2 mm T-S distance.

Material	Bluephase G2 LCU		Bluephase® turbo tip LCU		Bluephase Style LCU	
	Blue light (J/cm^2)	Violet light (J/cm^2)	Blue light (J/cm^2)	Violet light (J/cm^2)	Blue light (J/cm^2)	Violet light (J/cm^2)
Tetric bulk-fill	2.06 (0.13)	0.07 (0.03)	1.88 (0.1)	0.01 (0.02)	2.23 (0.18)	0.02 (0.03)
Filtek bulk-fill	2.03 (0.05)	0.15 (0.03)	1.91 (0.08)	0.07 (0.07)	1.25 (0.16)	0.58 (0.1)

The values are expressed as mean (standard deviation).

Table 5. The transmitted irradiance (mW/cm²) and TLE (J/cm²) and bottom/top TLE ratio (%) of both bulk-fill RBCs at different distances with the three LCUs

		Bluephase G2 LCU			Bluephase ®(turbo tip) LCU			Bluephase Style LCU		
		2 mm	6 mm	10 mm	2 mm	6 mm	10 mm	2 mm	6 mm	10 mm
Tetric bulk-fill	Transmitted Irradiance (mW/cm^2)	105.4 (6.23)	88.8 (6.69)	67.8 (3.63)	95 (4.64)	57.4 (2.07)	0 (0)	109 (8.31)	70.8 (6.53)	49.8 (0.84)
	Transmitted TLE (J/cm^2)	2.1^{AB*} (0.13)	1.76^{C} (0.14)	1.29^{D} (0.1)	1.89^{BC} (0.1)	0.95^{E} (0.12)	0^{G} (0)	2.25^{A} (0.18)	1.41^{D} (0.18)	0.5^{F} (0.09)
	Bottom/top TLE ratio (%)	$8.3\%^{HI}$ (0.01)	$6.6\%^{JK}$ (0.01)	$7.6\%^{IJ}$ (0.01)	$6.3\%^{JK}$ (0.003)	$7.4\%^{IJ}$ (0.01)	$0\%^{L}$ (0)	$9.2\%^{H}$ (0.01)	$7.2\%^{IJ}$ (0.01)	$5.3\%^{K}$ (0.01)
Filtek bulk-fill	Transmitted Irradiance (mW/cm^2)	110 (3.54)	92.2 (6.42)	66.6 (3.29)	99 (5.57)	56.4 (2.07)	0 (0)	90 (7.04)	65 (4.74)	0 (0)
	Transmitted TLE (J/cm^2)	2.19^{a} (0.07)	1.82^{b} (0.13)	1.21^{c} (0.12)	1.97^{ab} (0.12)	0.89^{d} (0.1)	0^{e} (0)	1.82^{b} (0.17)	1.19^{c} (0.15)	0^{e} (0)
	Bottom/top TLE ratio (%)	$8.7\%^{f}$ (0.003)	$6.8\%^{gh}$ (0.01)	$7.1\%^{gh}$ (0.01)	$6.5\%^{gh}$ (0.004)	$6.9\%^{gh}$ (0.01)	$0\%^{i}$ (0)	$7.4\%^{g}$ (0.005)	$6.1\%^{h}$ (0.05)	$0\%^{i}$ (0)

The values are expressed as mean (standard deviation).
*For each material, groups with the same superscript letters are not significantly different (Tukey's comparison test; P>0.05). The upper case letters demonstrate statistical comparisons within Tetric bulk-fill RBC while the lower case letters are for Filtek bulk-fill RBC.

Table 5 shows the mean irradiance and TLE transmitted through the samples of both materials at each T-S distance with each LCU.

The general linear model (GLM) indicated that there was a significant effect for the factors LCU type, T-S distance and material on the TLE transmission ($p<0.001$). The GLM further indicated that the interactions between LCU and material and LCU and distance also had a significant effect ($p<0.05$).

There was a significant reduction noted in the TLE transmitted through the samples of both materials with increasing T-S distance for all LCUs, the values at each T-S distance were significantly different *(Table 5)*, ($p<0.05$). The TLE (J/cm^2) is the mathematical product of irradiance (mW/cm^2) and exposure time(s). In this experiment, all the samples were cured for 20 seconds so the only factor that changed the TLE value was the light irradiance.

Within materials, comparison indicated that there was no significant difference in the mean transmitted TLE values with Bluephase G2 and Bluephase® (turbo tip) regardless of the type of material being tested ($p>0.05$). However, the mean TLE transmitted through Tetric bulk-fill was significantly greater than Filtek bulk-fill when cured with Bluephase Style ($p<0.05$). A further statistical investigation showed that this difference was significant at 2 mm and 10 mm T-S distances while it was not significant at 6 mm T-S distance.

The bottom/top TLE ratio (%) values were also significantly affected by the LCU and distance factors interaction ($p<0.05$) *(Table 5)* as well as the amount of TLE delivered to the top surfaces of the samples ($p<0.05$).

VICKERS HARDNESS

Table 6 shows the top and bottom surfaces VHN and VH ratios for both materials at the three distances with each LCU. The surfaces VHN of Tetric bulk-fill RBC were significantly greater than Filtek bulk-fill RBC ($p<0.05$). The top and bottom surfaces VHN of both materials were significantly affected by the distance and LCU factors interaction ($p<0.05$) and for each material, the amount of transmitted TLE had a significant effect on the VHN at the bottom surfaces of the samples ($P<0.05$).

For each material, the VH ratios were calculated against the maximum mean VHN achieved at the top surface of that material (i.e. 60.96 for Tetric and 40.24 for Filtek), these were considered to reflect the VHN of a 100% adequately cured surface for each material. The GLM indicated that there was a significant effect for the factors LCU type, T-S distance and material on the VH ratio ($p<0.001$). The GLM also indicated significant interactions between LCU and material, LCU and distance and material and distance ($p<0.05$). The mean VH ratio values decreased with increasing T-S distance *(Table 6)*. The rate of reduction depended on the LCU type *(Figure 2)*. When comparing the LCUs, similar VH ratio values were achieved by Bluephase G2 and Bluephase Style LCUs when the materials were cured at 2 mm or 6 mm T-S distance (p>0.05). The VH ratio values of the materials when cured at 10 mm T-S distance with Bluephase G2 were significantly greater than with either Bluephase® Turbo tip or Bluephase Style at the same distance (p<0.05) *(Table 6)*. The VH ratio values of the materials when cured with Bluephase® Turbo tip were lower than the values achieved by the other LCUs at each T-S distance.

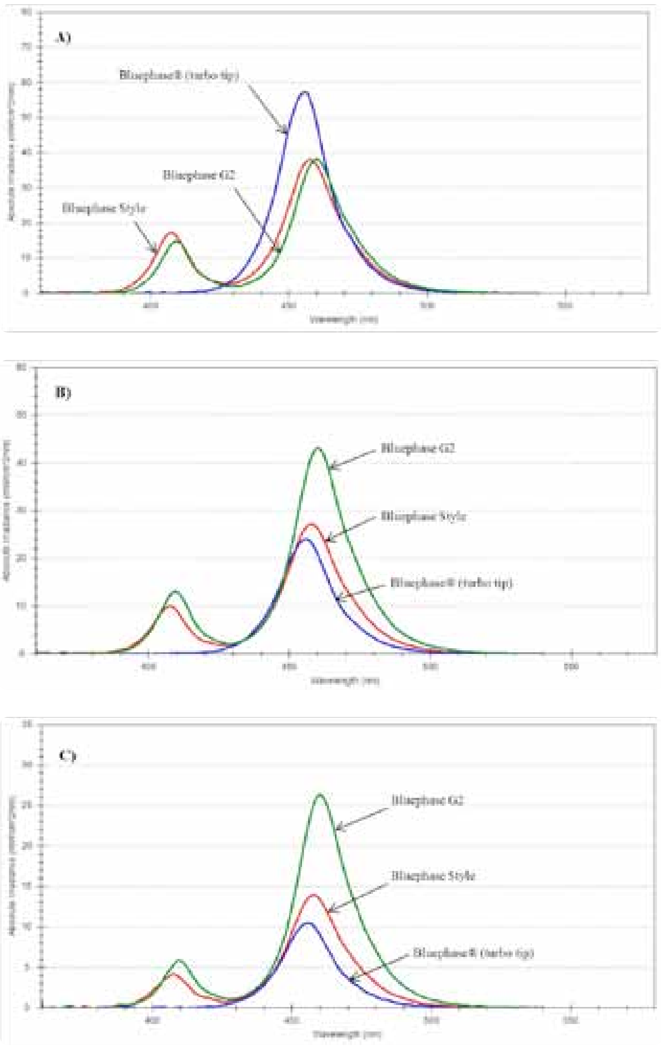

Figure 1: The emission spectra of the three used LCUs at the different T-S distances: A) at 2mm, B) at 6mm and C) at 10 mm.

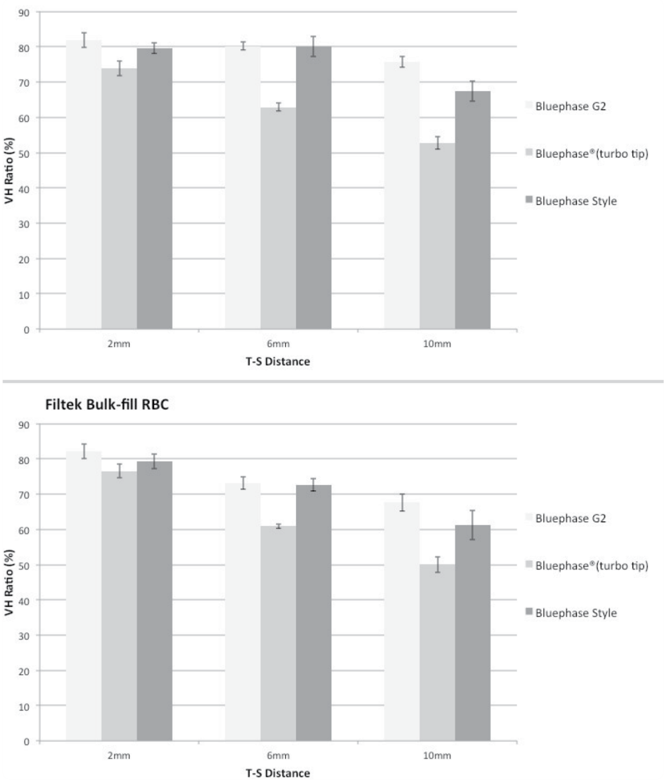

Figure 2: The mean VH ratio with each LCU at the different distances for each material

Statistical comparisons between the achieved VH ratio values from both materials with the different LCUs were made at 2mm T-S distance only *(Table 7)*. This revealed no significant differences in VH ratios between materials regardless of LCU type (p>0.05). For Tetric bulk-fill samples, curing with Bluephase G2 or Bluephase Style gave similar VH ratios (p>0.05) while both gave significantly higher VH ratios than when the samples of this material were cured with Bluephase® (turbo tip) (p<0.05). For Filtek bulk-fill samples, curing with Bluephase G2 or Bluephase Style also gave similar VH ratios (p>0.05), however, while Bluephase G2 gave significantly higher VH ratio value than with Bluephase® (turbo tip) (P<0.05), The VH ratio value with Bluephase Style was not significantly higher than the value achieved by Bluephase® (turbo tip) for this material (p>0.05).

DISCUSSION

LIGHT ENERGY TRANSMISSION

The results indicate that the irradiance delivered to the RBC samples from Bluephase® Turbo tip and Bluephase Style LCUs in the current experiment reduced as a function of T-S distance from 0 mm to 10 mm, these results are in agreement with multiple previous studies.[17, 21, 22, 27] The delivered irradiance from Bluephase G2 however, rose from 0mm to 6mm then declined *(Table 2)*. This LCU showed similar trend in a previous investigation.[28] The manufacturer of this LCU claims that this LCU in particular is designed with a maximum irradiance a short distance away from the specimen as in practice it is impractical to hold the light tip in contact with material.

Table 6. The top and bottom VHN and VH ratio of both bulk-fill RBCs at different distances with the three LCUs

		Bluephase G2 LCU			Bluephase ®(turbo tip) LCU			Bluephase Style LCU		
		2 mm	6 mm	10 mm	2 mm	6 mm	10 mm	2 mm	6 mm	10 mm
Tetric bulk-fill	Top VHN	59.68 (1.8)	58.84 (1.4)	57.58 (1.6)	53.08 (0.73)	47.36 (1.66)	43.86 (1.16)	58.9 (3.76)	60.96 (1.33)	57.62 (1.09)
	Bottom VHN	49.84 (1.27)	48.92 (0.66)	46.14 (0.93)	45.06 (1.27)	38.34 (0.65)	32.18 (1.12)	48.5 (0.94)	48.82 (1.79)	41.1 (1.76)
	VH ratio* (%)	81.8%^{A**} (2.1)	80.2% ^{A} (1.1)	75.7%^{BC} (1.5)	73.9%^{C} (2.1)	62.9%^{E} (1.1)	52.8%^{F} (1.8)	79.6%^{AB} (1.5)	80.1%^{A} (2.9)	67.4%^{D} (2.9)
Filtek bulk-fill	Top VHN	40.24 (0.39)	36.62 (0.78)	35.64 (1.09)	37.86 (0.57)	32.58 (1.03)	29.44 (0.45)	38.5 (0.57)	37.14 (0.9)	34.62 (0.74)
	Bottom VHN	33.04 (0.83)	29.4 (0.69)	27.2 (0.95)	30.82 (0.81)	24.52 (0.23)	20.06 (0.45)	31.9 (0.85)	29.24 (0.74)	24.62 (1.64)
	VH ratio (%)	82.2%^{a} (2.1)	73.1%^{c} (1.7)	67.6%^{d} (2.4)	76.6%^{bc} (2)	60.9%^{e} (0.6)	49.9%^{f} (2.2)	79. 3%^{ab} (2.1)	72.7%^{c} (1.8)	61.2%^{e} (4.1)

The values are expressed as mean (standard deviation).
*For each material, the VH ratios were calculated against the maximum mean VHN achieved at the top surface of that material.
**For each material, groups with the same superscript letters are not significantly different (Tukey's comparison test; P>0.05). The upper case letters demonstrate statistical comparisons within Tetric bulk-fill RBC while the lower case letters are for Filtek bulk-fill RBC.

Table 7. Statistical comparison between the mean VH ratios achieved within LCU and Material factors interaction at 2mm T-S distance (Tukey's test).

Comparison	Difference in mean VH ratio (%)	Confidence intervals	p-value*
Bluephase G2 with Tetric VS Bluephase G2 with Filtek	-0.35	-4.24 _ 3.55	>0.05
Bluephase Style with Tetric VS Bluephase Style with Filtek	0.29	-3.61 _ 4.18	>0.05
Bluephase® (turbo tip) with Tetric VS Bluephase® (turbo tip) with Filtek	-2.67	-6.57 _ 1.22	>0.05
Bluephase Style with Filtek VS Bluephase G2 with Filtek	-2.83	-6.73 _ 1.06	>0.05
Bluephase® (turbo tip) with Filtek VS Bluephase G2 with Filtek	-5.52	-9.41 _ -1.62	<0.05
Bluephase® (turbo tip) with Filtek VS Bluephase Style with Filtek	-2.68	-6.58 _ 1.21	>0.05
Bluephase Style with Tetric VS Bluephase G2 with Tetric	-2.20	-6.09 _ 1.70	>0.05
Bluephase® (turbo tip) with Tetric VS Bluephase G2 with Tetric	-7.84	-11.74 _ -3.95	<0.05
Bluephase® (turbo tip) with Tetric VS Bluephase Style with Tetric	-5.64	-9.54 _ -1.75	<0.05

*The difference is significant when p-value is <0.05

The three LCUs used in this study were selected because of their different behavior with increasing distance.[29] Bluephase G2 exhibited the lowest irradiance loss with increasing T-S distance. The Bluephase® fitted with a "turbo tip" light guide had the biggest reduction in irradiance over 10mm while the reduction in light irradiance with Bluephase Style was in between. In order to achieve a high power density, many curing lights are designed with a light guide with a reduced diameter emission window, the diameter of the "turbo" light guide of the Bluephase® decreases from 13 mm to 8 mm. This feature, however, has an adverse effect on the light scattering characteristics.[22, 30, 31] The scattering angle becomes wider and the light intensity decreases more rapidly as the distance grows larger. The Bluephase G2 is designed with a 10mm parallel light guide resulting in lower irradiance loss over distance compared to the 'turbo' light guide of Bluephase® as confirmed by our results *(Table 2*). The Bluephase Style is designed with a 10 mm shortened tip, a design that the manufacturer claims facilitates proper positioning of the LCU's tip over posterior restorations. However, according to our results, this design seems to increase light scattering with increasing T-S distance when compared to the parallel light guide of Bluephase G2.

To assess the light energy transmission through the samples in this study, it was preferred to prepare the samples in white Delrin® rings instead of metal rings as the former may behave in a more similar fashion to tooth structure toward light energy.[32] The use of Mylar strips to cover the top and bottom surfaces of the samples can affect light energy transmission.[3] In this study, to overcome this issue, Mylar strip was placed on sensor 1 while measuring the light irradiance delivered to the samples' top surface by each LCU *(Table 2*), thus standardising the amount of light delivered to the top surfaces of the samples which were covered with Mylar strips. The addition of another Mylar strip at the bottom surface of the samples did not show significant reduction in the amount of transmitted light in the preliminary tests.

Table 4 shows the spectral radiant power transmitted through the materials at 2 mm T-S distance and it shows that Filtek transmitted a higher proportion of violet light compared to Tetric samples. As mentioned earlier, Tetric bulk-fill RBC contains an additional photo-initiator (Ivocerin) which makes this material capable of absorbing the violet light. However, a more violet light was transmitted through the bottom surfaces of Tetric samples with Bluephase G2 *(Table 4*), which means that a more violet light reached the bottom surfaces of this material to cure Ivocerin. The Ivocerin absorption spectrum ranges between 370 to 460 nm and its absorption peak is at 408 nm.[7, 33] In contrast, Filtek bulk-fill RBC with only CQ photo-initiator,[3] has less ability to absorb violet light, therefore, a higher amount of violet light is transmitted through this material. CQ absorption spectrum ranges between 400 to 500 nm and its absorption peak is at 470 nm.[34, 35]

In this study, the amount of light transmitted through samples was significantly reduced with increasing T-S distance regardless of the type of LCU ($p<0.001$) used *(Table 5*). Interestingly, when the samples were cured with Bluephase Style, the mean TLE transmitted through Tetric samples were significantly higher than Filtek samples ($p<0.001$) while there were no significant differences when the samples of both materials were cured with the other LCUs. This significant difference was at 2 mm and 10 mm T-S distance but not significant at 6 mm.

Bluephase G2 and Bluephase Style are dual-peak light emitting dioide (LED) LCUs while Bluephase® (turbo tip) is single-peak LED LCU. The narrow emission spectrum of the single-peak LED LCUs is limited to 430 to 490 nm to match the absorption peak of CQ (470nm).[34] However, some manufacturers have added alternative photo-initiator(s) to their RBCs. The problem of these alternative photo-initiator(s) is that they need light at violet wavelengths to activate them effectively. In an attempt to overcome this problem, dual-peak LED LCUs have been introduced with a spectral output range between 380 to 515 nm.[36] Therefore, the dual-peak LCUs (Bluephase G2 and Bluephase Style) are able to emit violet light (360nm to 420 nm) and blue light (420 nm to 540 nm) while the single-peak LCU (Bluephase® (turbo tip)) emits only blue light as shown in Figure 1. Table 3 shows that Bluephase G2 and Bluephase Style LCUs have emitted different proportions of blue and violet lights at the different distances. The different amounts of light scattering from the blue and violet diodes at each T-S distance from these dual-peak LCUs is due to their less homogenous light distribution compared to single peak LCUs.[18]

When comparing Bluephase G2 and Bluephase Style profiles, both are very similar in terms of spectral irradiance, absolute irradiance and peak wavelengths both in violet and blue ranges *(Figure 1, Table 3*). However, Table 3 shows that Bluephase Style emitted slightly higher proportions of violet light and lower proportions of blue light than Bluephase G2. This finding was also reported in a previous investigation.[18] The main difference between Bluephase G2 and Bluephase Style is their different optical properties.[18, 37-39] Bluephase Style LCU has three LED emitters; two LED chips emitting blue light and one LED chip emitting violet light. These three LED chips are well separated leading to highly inhomogeneous distribution of irradiance and spectral emission across the tip of this LCU.[37, 38] In contrast, Bluephase G2 has four LED emitters; three emitting blue light and one emitting violet light. Bluephase G2 chips are located closer to each other when compared with the chips of Bluephase Style. It was reported that Bluephase G2 has inhomogeneous light as all dual-peak LCUs but it was less inhomogeneous than Bluephase Style.[18] Furthermore, Bluephase G2 has a unique feature i.e. during the soft-mode start (first three to five seconds of curing cycle) only the blue light emitting LED chips are powered, and no violet light is emitted.[39] Therefore, this difference in optical properties between these two LCUs could be a possible explanation for the significant difference found in the current study in TLE transmission between both tested materials when cured with Bluephase Style while no significant difference with Bluephase G2. With Bluephase Style, the TLE transmitted through Tetric samples was significantly higher than Filtek samples. The different interactions of these two materials with this LCU was also reported in another investigation.[38] Since Filtek bulk-fill RBC contains only CQ photo-initiator, it is more sensitive to less homogenous light than Tetric bulk-fill RBC which contains additional photo-initiator(s).

VICKERS HARDNESS

The extent of polymerization of the two bulk-fill RBCs was assessed by the determination of the VH ratio (%). Ideally the degree of polymerization of the RBC should be the same throughout its depth and the VH ratio (%) should be very close to or equal to 100%. However, as the light passes through the RBC, the amount of light is greatly reduced due to factors related to RBC material properties and the cure at the bottom surface is compromised.[40] The top surface of the RBC is usually well cured while the mechanical properties of the bottom surface are mostly reduced when insufficient light is applied.[16, 25]

In this study, the top and bottom surfaces of the samples were covered with a Mylar strip to prevent an oxygen inhibition layer and to get a smooth surface, as these are important to get accurate hardness measurement[41, 42] as well as to protect the MARC-RC™ sensor.[3] The VH test was performed twenty four hours after curing as it is considered that 'dark-cure' occurs for up to 24 hours post-irradiation.[43, 44]

The surfaces VHN of Tetric bulk-fill obtained in this study are significantly higher than Filtek bulk-fill. Tetric bulk-fill is a viscous material and it contains more filler than the flowable Filtek bulk-fill RBC,[3] so this result was expected and it coincides with the results of previous investigations.[3, 45, 46] However, the aim of this study was to compare the VH ratio values. The VH ratio values of the samples cured at 10 mm were significantly lower than the samples cured at 2 mm with all LCUs ($p<0.05$) *(Figure 2)*. This result is in agreement with multiple previous studies.[16, 47, 48] A reduction in the hardness ratio means a reduction in degree of polymerization. In this study, the reduction was different with each LCU *(Figure 2)*. Figure 2 shows that the VH ratio values at 2mm with Bluephase G2 and Bluephase Style for both materials are similar with no significant difference ($p>0.05$). For both materials at 10 mm T-S distance, the VH ratio values were significantly highest with Bluephase G2 LCU and lowest with Bluephase® (turbo tip) LCU ($p<0.05$). Bluephase G2 showed the least loss in irradiance with distance, which indicates that the light beam of this LCU is more collimated and has less divergence. In the literature, the LCUs with the least divergence in the light beam demonstrated the greatest degree of polymerization of RBCs at greater distance so this result is as expected.[17, 49]

Within materials comparison, the extent of polymerization of both tested materials with the different LCUs were compared at 2 mm T-S distance only *(Table 7)* as the different behavior of the three LCUs with distance might affects the statistical analysis. At 2 mm T-S distance there was no significant difference in VH ratio values between both materials with each LCU ($p>0.05$). In the light energy transmission results, there was a significant difference between both materials when cured with Bluephase Style at 2 mm T-S distance while the VH ratio values of both were not significantly different. In a previous study,[38] Filtek bulk-fill RBC gave non-symmetrical outcomes in the hardness across the surfaces compared to Tetric bulk-fill samples when cured with Bluephase Style. However, in the present study, curing Filtek samples with Bluephase Style did not adversely affect the VH ratio values at 2 mm T-S distance compared with the values of Tetric samples at the same distance. This could be due to the longer curing time of 20 seconds used in this study compared to the 10 seconds employed for the earlier study.[38] Therefore, this longer curing time might mask the effect of the highly inhomogeneous light from Bluephase Style on VH values. In the literature, a strong correlation has been reported between the inhomogeneous light output and the microhardness maps of the RBC surfaces.[37, 50] Using a LCU with an inhomogeneous light output can adversely affect localized microhardness values across the top and bottom surfaces of RBC samples.[37, 38] The local differences in irradiance distribution and inhomogeneous spectral output can affect the extent or the quality of cure across RBC specimen.[30, 32, 37, 38, 50] To overcome the effects of beam inhomogeneity of some LCUs, an increase exposure duration beyond manufacturers' recommended times has been suggested.[37] The manufacturer of Bluephase Style LCU (Ivoclar Vivadent) has recently introduced a light guide with a light homogenizer that reduces the light beam inhomogeneity of this LCU.

A better degree of polymerization can be achieved when the emission spectrum of the LCU matches the absorption spectrum of the RBC's photo-initiator. For both tested materials the VH ratio values was less with the single-peak Bluephase® (turbo tip) LCU compared with the other LCUs, even at 2 mm T-S distance where the samples received the greatest TLE from Bluephase® (turbo tip) LCU *(Table 2)*, the VH ratio values were less than the values achieved with other LCUs at the same distance *(Table 6)*, indicating that not only the quantity of light energy but also the quality is important (i.e. the proper match between the photo-initiator absorption spectrum and the spectral output of the LCU and the light beam homogenity). For both materials, the best VH ratio values were achieved when the samples were cured with Bluephase G2 LCU. This might support the manufacturer's claim that this LCU is capable of curing a wide range of RBCs. The VH ratios of Tetric samples were better with dual-peak LCUs and this was expected as this RBC contains additional photo-initiator(s). However, it was expected that Filtek samples would have good VH ratio results with the single peak Bluephase® (turbo tip) LCU since it contains only CQ photo-initiator but this was not shown in this experiment. This could be due to the tip design of this LCU. It was reported that LCUs with turbo tips have less homogenous intensity distribution which adversely affects hardness measurements especially at bottom surfaces of RBCs.[30] Therefore, the interactions between different factors like LCU's tip design, light irradiance, spectral output and material properties will affect the degree of polymerisation of any RBC.[30, 32, 38]

The results of this study show that the degree of polymerization reduced with increasing T-S distance. In this study the LCU's tip was always perpendicular to the samples' top surface. However, in clinical situations, the curing light is not only attenuated by distance but also by the angle of the tip of the LCU to the RBC.[51]

TOTAL LIGHT ENERGY

Clinicians are not given enough information regarding the light energy requirement for polymerization of composite resins. Some manufacturers state how much light energy is required in their product information documents. Most recommend a curing time and state the tip irradiance data of their LCU. It is not LCU tip irradiance, however, that determines how well a resin is cured. Adequate polymerization of RBCs correlates strongly with the light energy delivered.[25] The total light energy (J/cm^2) is the mathematical product of irradiance (mW/cm^2) and exposure time(s). Therefore, according to the manufacturer's instructions, the minimum amount of TLE required to adequately cure Tetric bulk-fill RBC is 10J/cm^2. For Filtek bulk-fill RBC, the minimum TLE required is 22J/cm^2 with any halogen or LED LCUs. In this study, Tetric bulk-fill RBC showed a VH ratio of nearly 80% or more when it was cured with Bluephase G2 and Bluephase Style at 2 mm and 6 mm T-S distances. The TLE at these distances ranged between 26.85 to 19.51 J/cm^2 . For Filtek bulk-fill RBC, this was achieved when it was cured with either Bluephase G2 or Bluephase Style at a 2 mm T-S distance with TLE values from 25.2 to 24.54 J/cm^2. The results of this study shows that both materials require longer irradiation times than those recommended by the manufacturers. However, for both materials, a VH ratio of 80% was not achieved when these materials were cured with Bluephase® (turbo tip) at the three tested distances even at 2 mm T-S distance where the samples received a TLE of 30.17 J/cm^2. This emphasizes the claim that calculations based on TLE delivered to guide irradiation protocols are invalid[52] as they do not recognize individual product characteristics such as the materials photo-initiator and shade (absorption spectrum), light source (emission spectrum) and filtration (transmission spectrum). The VH ratio results of this study emphasise the importance of appropriate selection of LCUs for the dental materials to ensure better polymerization and therefore, better restoration longevity.[53]

CONCLUSION

In conclusion, the current study showed significant reduction in both the light energy transmitted through the samples and their VH ratios with increasing T-S distance, therefore both null hypotheses were rejected. However, the rate of decline in VH ratio was different with the different LCUs tested. The least reduction in VH ratio with increasing T-S distance was obtained with Bluephase G2 LCU. In addition, this study emphasizes the importance of the appropriate matching between LCU type and RBC for better material polymerization.

CLINICAL IMPLICATIONS

Clinicians must take care while curing the RBC to keep the LCU's tip very close to the surface of the RBC restoration. However, in some clinical situations it might be difficult to position the LCU's tip close to the restoration surface. Therefore, in such situations, it is advisable to use an LCU like Bluephase G2 as according to the results of this study, the VH ratio is likely to be compromised less with increasing T-S distance compared to other LCUs. Also, increasing the curing time might lessen the effect of large T-S distances.

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MANUFACTURERS' DETAILS

- MARC-Resin Calibrator™ (BlueLight analytics inc., Halifax, NS, Canada), incorporating a spectral radiometer (USB 4000, Ocean Optics, Dunedin, FL, USA), with a 3,648-element linear CCD array detector (TCD1304AP, Toshiba, Tokyo, Japan).
- MARC™ custom software (24/7, Halifax, NS, Canada).
- Filtek Bulk-Fill Restorative Material (3M™ ESPE™, U.S.A).
- Tetric EvoCeram Bulk-Fill Restorative Material (Ivoclar Vivadent AG, Schaan, Liechtenstein).
- Delrin® rings (DuPont, Mississauga, Ontario, Canada).
- Mylar strip (KerrHawe SA, Bioggio, Switzerland).
- Single-peak Bluephase (second generation) LED LCU with turbo tip (Ivoclar Vivadent AG, Schaan, Liechtenstein); Serial no. 1614337.
- Dual-peak Bluephase G2 (third generation) LED LCU (Ivoclar Vivadent AG, Schaan, Liechtenstein); Serial no. 215502.
- Dual-peak Bluephase Style (third generation) LED LCU (Ivoclar Vivadent AG, Schaan, Liechtenstein); Serial no. 1100001298.
- Micro Vickers Hardness Testing Machine (HM-200 Series, Mitutoyo, Japan)
- Minitab 17 (Minitab Inc., State College, PA, USA).

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