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Laboratory Research

Effect of Mold Type and Diameter on the Depth of Cure of Three Resin-Based Composites

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Clinical Relevance

Wide multisurface composite restorations may achieve a greater depth of cure than a narrower restoration, especially when a less opaque matrix is used. Clinicians should not attempt to light cure a 4 mm increment of conventional composite, even with an increased exposure time.

SUMMARY

Objective: To evaluate the effects of different mold materials, their diameters, and light-curing units on the mechanical properties of three resin-based composites (RBC).

Methods and Materials: A conventional nano-filled resin composite (Filtek Supreme Ultra, 3M Oral Care, St Paul, MN, USA) and two bulk-fill composites materials, Tetric Evoceram Bulk fill (Ivoclar Vivadent, Schaan, Liechtenstein) and Aura Bulk Fill (SDI, Bayswater, VIC, Australia), were tested. A total of 240 specimens were fabricated using metal or white semitransparent Delrin molds that were 4 or 10 mm in diameter. The RBCs were light cured for 40 seconds on the high-power setting of either a monowave (DeepCure-S, 3M Oral Care) or polywave (Bluephase G2, Ivoclar Vivadent) light-emitting diode (LED) curing unit. The depth of cure was determined using a scraping test, according to the 2009 ISO 4049 test method. Data were analyzed using multivariate analysis of variance followed by Tukey multiple comparison test ($p<0.05$).

Results: In general, when used for 40 seconds, both LED curing lights achieved the same depth of cure ($p=0.157$). However, the mold material and its diameter had a significant effect on the depth of cure of all three RBCs ($p<0.0001$).

Conclusion: Curing with either the polywave or monowave LED curing light resulted in the same depth of cure in the composites. The greatest depth of cure was always achieved using the 10-mm-diameter Delrin mold. Of the three RBCs tested, both Tetric Bulk Fill and Aura achieved a 4-mm depth of cure when tested in the 10-mm-diameter metal mold. Tetric Bulk Fill was the most transparent and

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had the greatest depth of cure, and the conventional composite had the least depth of cure. Very little violet (<420 nm) light penetrated through 6 mm of any of the RBCs.

INTRODUCTION

Photopolymerizable resin-based composites have become the material of choice for direct restorations, and as a consequence of the recommendations of the 2013 Minamata agreement, they are replacing dental amalgam.[1] Using a resin-based composite (RBC) allows for more conservative tooth preparation designs, improved reparability, and an esthetic tooth-colored restoration.[2]

Resin-based composites are highly cross-linked polymeric materials that contain pigments and filler particles that determine their final properties.[3,4] While the resin matrix is considered to be the skeleton of the RBC, the inorganic fillers improve wear resistance, reduce polymerization shrinkage, reduce the coefficient of thermal expansion, and reduce water absorption.[3]

Camphorquinone (CQ) is the most commonly used photoinitiator, with ethyl-4-(N, N-dimethyl-amino) benzoate often used as an amine co-initiator. CQ is activated by a broad range of light but is most sensitive to blue light at approximately 468 nm, and also to light below 320 nm. Thus, CQ allows photopolymerization of the resin after it has been irradiated with blue light from a dental curing unit that delivers light in the 400- to 500-nm wavelength range.[3]

To overcome some of the yellow color–related side effects of using CQ as a photoinitiator, some light-shaded or translucent RBCs also include alternative photoinitiators such as 2,4,6-trimethylbenzoyldiphenylphosphine oxide (TPO), 1-phenyl-1,2-propanedione (PPD), or the germanium based initiator, Ivocerin.[5] Improved color stability and a higher degree of conversion has been reported for RBCs that contain TPO.[6,7] The PPD initiator is sometimes used in combination with CQ to reduce its yellowing effects, enhance the photoinitiation reaction, and possibly reduce the polymerization stress that is produced by the cured RBC.[8,9] The dibenzoyl-germanium compound, Ivocerin, has a higher photoinitiation activity and also absorbs visible light over a wider range of wavelengths (from 370 to 460 nm).[10,11]

The maximum degree of conversion (DC) for light activated dimethacrylate polymers is never 100%, but instead, it ranges between 43% and 75% depending on the brand of RBC and measurement method.[12] Ideally, the RBC should achieve a high degree of monomer conversion so that the manufacturer's desired physical properties and the most biocompatible RBC are achieved in the tooth.[13,14] The depth of cure (DOC) of the RBC can be affected by many factors, including exposure time, radiant exposure, the type of the light-curing unit used, thickness of RBC, its volume, and the type of photoinitiator used within the RBC.[15,16]

Although considered to be the gold standard, incremental placement of 2-mm-thicknesses of RBC is time-consuming. Incremental placement also increases the chance of void incorporation and contamination between each layer of RBC.[17,18] To reduce placement time, reduce the possibility of contamination between increments, minimize polymerization shrinkage, and allow improved polymerization at greater depths, bulk-fill RBCs have been introduced.[18] These bulk-fill materials should provide adequate curing of 4- to 5-mm-thick increments of RBC.[11,19] This is due to the use of improved photoinitiator systems, improved matching of the refractive indices between the resin and the filler, and overall increased translucency of the matrix that allows greater penetration of light down into the deeper areas of the RBC.[20]

Different types of light-curing units (LCU) are available, such as the conventional quartz tungsten halogen (QTH), plasma arc, and light-emitting diode (LED) curing light units.[21] QTH units emit a broad spectrum of light from 400-500 nm that is compatible with the most commonly used photoinitiator, CQ, and all newer generations of photoinitiators.[22] However, QTH units have several limitations: the high operating temperature of the QTH bulb, a short life span for the QTH bulb of only about 50 working hours, and a relatively large device size.[23] In the mid-1990s, the first generation of LED curing lights was introduced.[24] These LED units emitted blue light in a narrow range of wavelengths that were compatible with the activation range of CQ.[25,26] The LED emitter should last for thousands of hours, and they can be battery powered (cordless).[25] Consequently, the use of QTH units has fallen, and battery-operated LED units now dominate the market. The first generation of LED units delivered only a low power output, and their curing efficacy was questionable until the next generation of higher-power LED units was developed.[27] These LED LCUs deliver equivalent or higher powers than the QTH units, and some of them emit light in two or more different wavelength ranges (they are sometimes called third-generation broad-spectrum or polywave LED LCUs). These units produce both violet (shorter) wavelength and blue (longer) wavelengths of light from two or more different LED emitters located within the unit. The violet light is used to activate photoinitiators that are most sensitive to light that is shorter than 420 nm in wavelength,[7,28] whereas the blue light activates the CQ photoinitiator.[28] Therefore, these polywave LED LCUs can activate all of the currently used photoinitiators.[7,29] Santini and others[30] reported higher DC values in 2-mm-thick specimens of RBCs that contained the TPO photoinitiator when cured with a polywave LED LCU compared with when a monowave LED LCU was used. On the other hand, when Menees and others,[31] in 2015, evaluated the DOC of Tetric Evoceram Bulk Fill and Filtek Bulk Fill Posterior RBCs cured with either a monowave (Elipar S10 delivering 13.5 J/cm^2) or a polywave (Bluephase G2 delivering 10.9 J/cm^2) LCU, they found that Tetric Evoceram Bulk Fill showed a deeper DOC than Filtek Bulk Fill Posterior in a 4 mm wide metal mold, but not in a tooth mold. They found no statistically significant effect of the different LED LCU types on the DOC, despite the different photoinitiators used within the RBCs. This result was surprising because according to the manufacturer, the polywave LCU should be expected to better activate the Ivocerin photoinitiator used in Tetric Evoceram Bulk Fill and provide an improved DOC.[31] A similar result was reported in 2016 by Issa and others,[32] who tested the nanohardness and elastic modulus of Tetric Evoceram Bulk Fill RBC cured with polywave LED LCUs in 6-mm-diameter metal molds. Their study design allowed them to determine which wavelengths were delivered to different regions of the test specimens, and they found no differences in the tested properties of Tetric Bulk Fill to a depth of 4 mm when mostly lower-wavelength violet light was delivered compared with when mostly longer-wavelength blue light was delivered. However, it was reported that delivering mostly lower-wavelength violet light adversely affected the DOC of Filtek Bulk Fill flowable (FBFF,) whereas delivering mostly longer-wavelength blue light improved the properties of FBFF.[32]

Clearly, study methodology has an impact on the DOC of RBCs. A previous study in 1993 by Harrington and Wilson[33] tested the DOC of RBCs using white polytetrafluoroethylene, black Nylotron, and stainless-steel mold materials of 4-mm diameter. A greater DOC was found with white molds.[33] Similarly semitransparent white Delrin molds may better mimic the optical properties of tooth than the completely opaque stainless-steel mold that is used in the 2009 ISO 4049 standard.[34] However, there are many different types and opacities of Delrin, and an opaque metal mold has some advantages. Rueggeberg and others,[34] in 2016, evaluated RBCs DOC using different mold materials and diameters. The RBCs were packed in one increment into split Delrin or metal stainless-steel molds that had either 4-, 6-, or 10-mm diameter holes. They reported that RBCs cured within white Delrin molds showed greater DOC than RBCs that were photocured in metal molds. Of note, increasing the mold diameter resulted in greater DOC values. They concluded that the mold material and diameter both have a significant impact on the DOC, but they used only one brand of bulk-fill RBC.[34]

The International Standards Organization (ISO) provides guidelines for laboratory studies to test the properties of dental polymer–based restorative materials.[35] According to ISO 4049:2009, the material should be cured within a stainless-steel mold that should be 4 mm in diameter and at least 2 mm longer than twice the claimed DOC.[20] Immediately after curing the RBC from the top, the soft uncured RBC at the bottom is scraped away using a plastic instrument. The maximum length of hard RBC is measured and divided by two to determine the DOC.[36] Contemporary bulk-filling RBCs are intended to be used in cavities that are much greater than this 4-mm diameter, and thus, the 4-mm-diameter mold specified in ISO 4049 may not be applicable when testing bulk-fill RBCs, but this requires confirmation.

This *in vitro* study investigated the effect of two mold materials (metal vs white semitransparent Delrin), the diameters of the tested specimens, and types of LCU on the DOC of three RBCs. The null hypotheses of this *in vitro* study were the following:

1) There will be no difference in the DOC of the three tested composite materials when made in the metal mold specified in the ISO 4049 test compared with a similar mold made of Delrin.
2) There will be no difference in the DOC of the three tested composite materials when made in the 4-mm mold specified in the ISO 4049 test compared with the larger 10-mm-diameter mold.
3) There will be no difference in the DOC of the three tested composite materials when either a high-power polywave LED or high-power monowave LED LCU is used.

Table 1: *Resin-Based Composite Resins and Light-Curing Units Used in the Study*

Material (Shade)	Type	Manufacturer	Lot No.
Filtek Supreme Ultra (2AB)	Conventional	3M ESPE, St Paul, MN, USA	N751605
Tetric EvoCeram Bulk Fill (IVA)	Bulk fill	Ivoclar Vivadent, Schaan, Liechtenstein	U55063
Aura Bulk Fill (BKF)	Bulk fill	SDI, Australia	151614
Bluephase G2	LED Polywave	Ivoclar Vivadent, Schaan, Liechtenstein	222788
Elipar DeepCure-S	LED Monowave	3M ESPE, St Paul, MN, USA	932125

4) There will be no difference in the transmission of the lower wavelengths (violet) of light through all three RBCs.

METHODS AND MATERIALS

Three RBCs were evaluated: two bulk-fill RBCs (Tetric Evoceram Bulk Fill shade IVA [Ivoclar Vivadent, Schaan, Liechtenstein] and Aura Bulk Fill universal shade [SDI, Bayswater, VIC, Australia]) and one conventional nano-composite RBC that is intended to be used in at most a 2 mm increment (Filtek Supreme Ultra shade A2B, 3M Oral Care, St Paul, MN, USA; Table 1). Metal (M) and semitransparent white Delrin (D) split molds of 15-mm depth and a 4- or 10-mm internal diameter opening were used to prepare the composite specimens (Figure 1).[35] The molds were placed on a polyester strip over a glass slide, and then uncured RBC was packed in one increment into the mold. A polyester strip was used to cover the uncured RBC in the mold. The RBCs were then light cured using either the polywave LED (Bluephase G2, Ivoclar Vivadent) or the monowave LED (Elipar DeepCure-S, 3M Oral Care) for 40 seconds, with the curing tip perpendicular to the mold surface and centered directly over the opening (Table 1). To standardize exposure times and to deliver sufficient radiant exposure, the same 40-second exposure time recommended by the manufacturer of Aura was used for both lights and all RBCs.

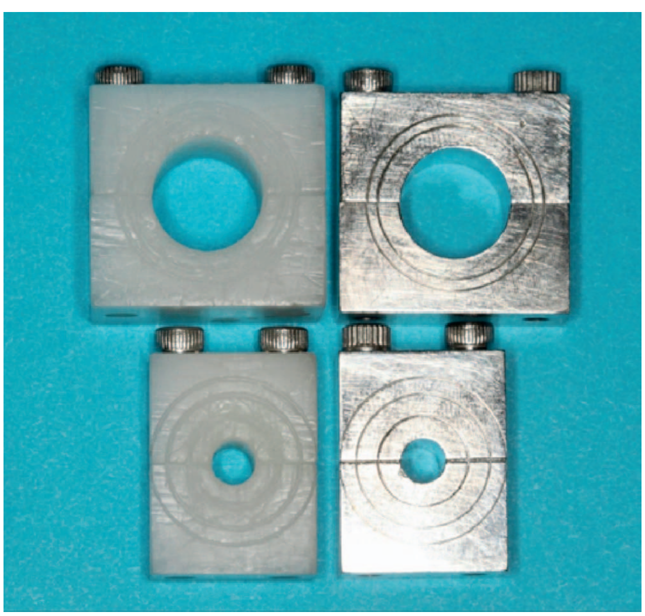


Figure 1. *Split molds (Delrin and metal) with a 4- and a 10-mm internal diameter.*

The irradiance, radiant exposure, and spectral emission from the two LCUs were measured using a 6-inch integrating sphere (Labsphere, North Sutton, NH, USA) connected to a fiber-optic spectrometer (USB 4000, Ocean Optics, Dunedin, FL, USA). This fiber-optic system was calibrated before the experiment using the internal reference lamp contained within the sphere. The output from each LCU was measured through both a 10-mm-diameter aperture and a 4-mm-diameter aperture placed at the entrance to the integrating sphere. The 10-mm-diameter aperture matched the diameter of the end of the light guides, and the 4-mm-diameter aperture matched the diameter of the 4-mm molds. Thus, in this case, the sphere measured the same spectral radiant power that would be received by the 4-mm specimens and not the total output emitted from the LCU. Spectrasuite v2.0.162 software (Ocean Optics) was used for data collection and analysis. These data were considered as the control values for the light reaching the RBCs.

Immediately after light exposure, the RBC specimens were removed. The uncured RBC was manually scraped away using a plastic spatula, the maximum length of the remaining hard, cured resin measured to the nearest 0.01 mm using a digital caliper (Mitutoyo, Canada Inc, Mississauga, ON, Canada) and the values divided by two according to the ISO 4049 test method.[20] A total of 240 specimens were prepared (two mold materials × two diameters × three RBCs × two LEDS × 10 repeats). A random sequence of RBC material, mold size and type, and LED unit was used to make 10 specimens for each condition.

Light Transmission Through the RBCs

The amount of light transmitted through a standard 6-mm-long specimen of each cured RBC was measured. This length was chosen because it was the length of hard specimens that could be consistently obtained. The spectral radiant power emitted from the bottom of the 6-mm thick specimens of RBC in the respective molds was measured using a 6-inch integrating sphere (Labsphere) connected to a fiber-optic spectrometer (USB 4000, Ocean Optics). This fiber-optic system was calibrated before the experiment using the internal reference lamp contained within the sphere. Spectrasuite v2.0.162 software (Ocean Optics) was used for data collection and analysis.

Statistical Analysis

Data were analyzed using SPSS Pc + version 21.0 (IBM Inc, Chicago, IL, USA) statistical software. Descriptive statistics (mean and standard deviation) were used to describe the quantitative outcome variable (RBC DOC). The data were tested graphically and by homogeneity of variances, to determine whether the data were normally distributed. Multivariate analysis of variance (ANOVA) was used to compare the mean values of DOC, in relation to three RBCs, two mold materials, two diameters, and two LED LCUs. Multivariate ANOVA followed by post hoc Tukey multiple comparison tests were used to assess the significance (α=0.05) of each study variable in relation to the DOC values.

RESULTS

Although not detectable by the human eye or by a dental radiometer, the Elipar DeepCure-S delivered different emission spectra from the Bluephase G2. The Elipar DeepCure-S delivered a higher power compared with the Bluephase G2 through the 4-mm-diameter aperture, 256 mW compared with 166 mW for the G2. When measuring power through a 10-mm-diameter aperture, both LEDs delivered similar power values, with the polywave LED curing light delivering 820 mW and the monowave LED curing light delivering 807 mW. There was a statistically significant difference for three variables tested (RBC, mold type, and LCU; Table 2).

Effect of RBC Type on the DOC

There was significant difference in the mean values of DOC in relation to the three RBCs. Tetric Evoceram Bulk-Fill composite showed the greatest mean DOC value compared with the other two RBCs, namely, Aura and Filtek Supreme Ultra (Table 2). The conventional material Filtek Supreme Ultra showed the least DOC ($p<0.0001$).

Effect of Mold Material and Diameter on DOC

There was a statistically significant difference in mean depth cure values between the two mold materials and the two mold diameters (Table 2). The white Delrin mold material always produced a significantly greater DOC compared with the metal mold ($p<0.0001$). Also, significantly higher DOC was always found in the molds that had a 10-mm internal diameter compared with the molds with the 4-mm internal diameter ($p<0.0001$).

Effect of LED Type on DOC

There was no statistically significant difference in the mean DOC values when either the Bluephase G2 or DeepCure-S ($p=0.157$) were used for 40 seconds (Table 2).

Light Transmission Through the RBCs

When using the Deep Cure-S, at the bottom of the 6-mm-long cured specimen of each brand of RBC, approximately 0.4% (Supreme Ultra), 1.9% (Aura), and 2.6% (Ivoclar Bulk Fill) of the original amount of light was transmitted when using the 10-mm-diameter metal mold, and approximately 0.2% (Supreme Ultra), 0.9% (Aura), and 1.5% (Ivoclar Bulk Fill) when using the 4-mm-diameter metal mold (Figure 2). As for the 10-mm-diameter Delrin mold, approximately 0.5% (Supreme Ultra), 2.2% (Aura), and 2.9% (Ivoclar Bulk Fill) of the original amount of light was transmitted, compared with approximately 3.3% (Supreme Ultra), 5.2% (Aura), and 6.2% (Ivoclar Bulk Fill) when using the 4-mm-diameter Delrin mold (Figure 2).

When using the Bluephase G2, at the bottom of this 6-mm-long cured specimen of each brand of RBC, approximately 0.4% (Supreme Ultra), 1.9% (Aura), and 3.1% (Ivoclar Bulk Fill) of the original amount of light was transmitted when using the 10-mm-diameter metal mold and approximately 0.2% (Supreme Ultra), 1.0% (Aura), and 1.5% (Ivoclar Bulk Fill) when using the 4-mm-diameter metal mold (Figure 3). As for the 10-mm-diameter Delrin mold, approximately 0.6% (Supreme Ultra), 2.4% (Aura), and 3.5% (Ivoclar Bulk Fill) of the original amount of light was transmitted, compared with approximately 4.6% (Supreme Ultra), 7.0% (Aura), and 8.3% (Ivoclar Bulk Fill) when using the 4-mm-diameter Delrin mold (Figure 3). For all three RBCs,

Table 2: *Depth of Cure (Means and SDs) of Different Resin-Based Composites When Cured With the Bluephase G2 or the DeepCure-S Curing Lights in the 4-mm and 10-mm Delrin and Metal molds* [a]

Resin-Based Composites	Mean Depth of Cure ± SD, mm				Multivariant ANOVA Test	
	Group			Mean ± SD		
	Curing Light	Mold Type	Diameter, mm			
Aura Bulk Fill	Bluephase G2	Delrin	4	$5.04 \pm 0.03_e$	Resin-based composite	<0.0001
			10	$6.16 \pm 0.19^{**}_j$		
		Metal	4	$3.98 \pm 0.09^{*}_c$		
			10	$5.03 \pm 0.02_e$		
	DeepCure	Delrin	4	$5.06 \pm 0.04_e$		
			10	$5.81 \pm 0.09_h$		
		Metal	4	$4.1 \pm 0.08_c$	Curing light	0.157
			10	$4.98 \pm 0.03_e$		
Filtek Supreme Ultra A2B	Bluephase G2	Delrin	4	$5.02 \pm 0.02_e$		
			10	$5.27 \pm 0.09^{**}_g$		
		Metal	4	$3.42 \pm 0.07^{*}_a$		
			10	$4.09 \pm 0.04_c$		
	DeepCure	Delrin	4	$5.04 \pm 0.02_e$	Mold material type	<0.0001
			10	$4.80 \pm 0.08_f$		
		Metal	4	$3.61 \pm 0.08_b$		
			10	$3.99 \pm 0.06_c$		
Tetric Bulk Fill IVA	Bluephase G2	Delrin	4	$5.04 \pm 0.02_e$		
			10	$6.73 \pm 0.12^{**}_l$		
		Metal	4	$4.36 \pm 0.17^{*}_d$	Mold diameter	<0.0001
			10	$5.09 \pm 0.02_e$		
	DeepCure	Delrin	4	$5.08 \pm 0.05_e$		
			10	$6.68 \pm 0.19_l$		
		Metal	4	$4.78 \pm 0.16_f$		
			10	$5.11 \pm 0.03_e$		

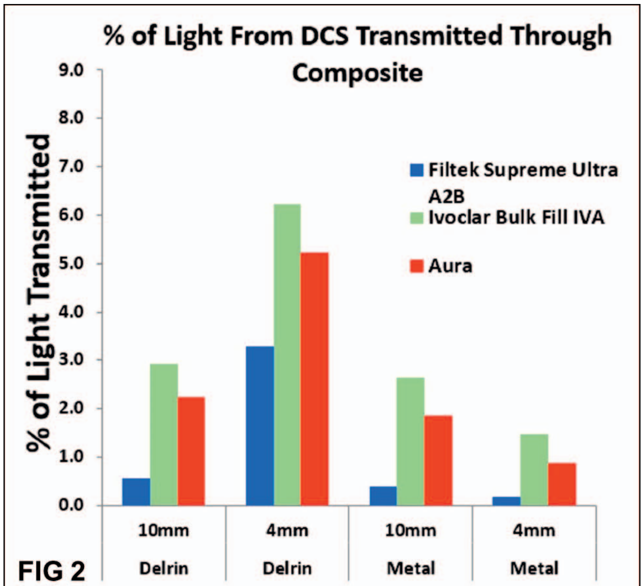
[a] *Maximum length divided by 2 as per ISO 1049. n=10 for each group; significant difference at $p<0.05$. According to post hoc Tukey multiple comparison test, means with the same subscript letter are not statistically different and means with different subscript letters are statistically different.*
** Lowest mean values for each RBC.*
*** Highest mean values for each RBC.*

the lower wavelengths of light (below 420 nm) were almost completely filtered out after passing through 6 mm of cured resin (Figure 4).

DISCUSSION

This *in vitro* study evaluated the effect of two different mold materials and mold diameters on the DOC of two bulk-fill RBCs (Tetric Bulk Fill and Aura Bulk Fill) and one conventional nanofilled-resin composite that is recommended to be used in at most a 2 mm increment (Filtek Supreme Ultra). The 4-mm-diameter metal molds were the molds specified in the ISO 4049 standard. There was a significant difference when using the semitransparent white Delrin compared with the metal molds. The Delrin material always resulted in a greater DOC for all tested RBCs ($p<0.0001$). Thus, the first null hypothesis was rejected. The second null hypothesis that different diameters of molds will have no significant effect on the DOC on the three RBC materials was also rejected, because the wider mold diameter (10-mm internal diameter) always produced a greater DOC when compared with the 4-mm internal diameter molds ($p<0.0001$). With regard to the third hypothesis, there were no differences ($p=0.157$) between curing either with the monowave or polywave LED when they were used for 40 seconds, and therefore, this hypothesis was accepted. The lower wavelengths of light (below 420 nm) were almost completely filtered out after passing through 6 mm of all three RBCs, and the fourth hypothesis was accepted (Figure 4).

With regard to the effect of different mold types on curing RBCs, our study found that the DOC results



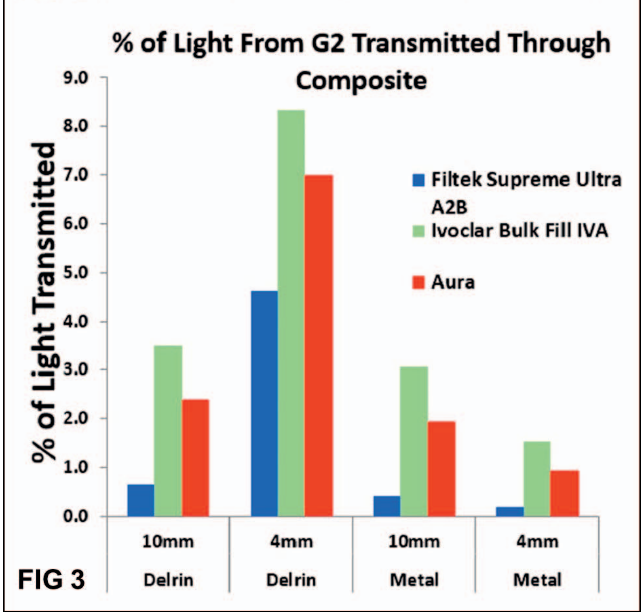


Figure 2. *DeepCure-S: Percentage of light delivered to the surface emitted from the bottom of 6-mm-thick cured specimens of each RBC in the 4- and 10-mm-diameter Delrin and metal molds.*

Figure 3. *Bluephase G2: Percentage of light delivered to the surface emitted from the bottom of 6-mm-thick cured specimens of each RBC in the 4- and 10-mm-diameter Delrin and metal molds.*

for both a conventional and a bulk-fill RBC made in the Delrin mold were always greater than those made in the metal mold. This was in agreement with other studies and suggests that the 4-mm metal mold specified in the 2009 ISO 4049 specifications will underestimate the DOC that will occur in a large tooth restoration.[34,37] This reduction in the DOC when smaller-diameter molds are used has been previously reported and is believed to occur because

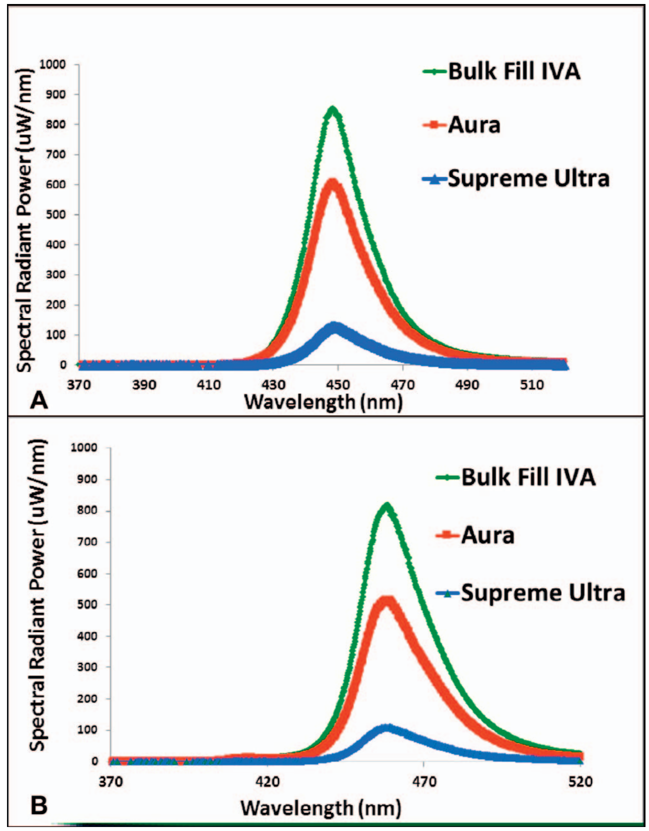


Figure 4. *Spectral radiant power (uW/nm) from the DeepCure-S (a) and the Bluephase G2 (b) emitted from the bottom of the 6-mm-thick specimens of RBC (note the absence of the lower wavelengths of light below 420 nm from the G2).*

the metal mold walls prevent any light transmission from the mold into the RBC, thus resulting in lower DOC.[34,37] In addition, the top surface area of the 4-mm-diameter mold was 12.56 mm^2, whereas the top area of the 10-mm-diameter cylinder was 78.50 mm^2. Thus, the 10-mm-diameter mold would allow 6.25 times as much light to enter into the mold, and this likely also improved the DOC of the RBCs. When using a bulk-fill RBC, Rueggeberg and others[34] also reported greater DOC for RBCs cured with Delrin molds when compared with metal stainless-steel molds.[34] In a different study, Erickson and Barkmeier[37] also reported lower DOC of a conventional RBC (Z100, 3M Oral Care) cured within opaque mold materials. A possible clarification of this finding is that the DOC is influenced by the light absorption and/or reflection properties of different mold materials. The white Delrin mold allows light to be transmitted down the sides of the mold in addition to light passing through the RBC, and thus, more light is received than from just the top alone. Since more light energy is delivered to the RBC specimens, and a greater DOC occurs.[34,37]

The Bluephase G2 delivered a slightly greater radiant power compared with the Deep Cure-S (820 mW compared with 807 mW), but the increased power and the different wavelengths of light from the polywave LED curing light did not produce a statistically significant difference (p=0.157) in the DOC of the three RBCs. A possible explanation is the large amount of energy delivered to the RBCs, because both LCUs were used for 40 seconds. The radiant power that arrived at the top of the 10-mm-diameter specimens was 820 mW for the G2 light and 807 mW for the Deep Cure-S light. In contrast, the radiant power that arrived at the top of the 4-mm-diameter specimens was less (166 mW) for the Bluephase G2 light compared with 256 mW for the DeepCure-S light. Although the Bluephase G2 was a more powerful light, the lower radiant power delivered to the top of the 4-mm-diameter specimens by the Bluephase G2 was likely due to the relative inhomogeneity in the light output from this LCU compared to the DeepCure-S. Whereas there is only one emitter in the DeepCure-S, the Bluephase G2 uses four LED emitters to deliver light in two different wavelength ranges. The location of these four emitters and the reflector produces an inhomogeneous light output, thus explaining why the 4-mm-diameter specimens received less light.[38] This difference in the radiant power delivered to the 4-mm-diameter specimens from the Bluephase G2 compared with the DeepCure-S probably accounts for the 20.55% increase in the DOC for the Bluephase G2 samples made in the 10-mm-diameter (regardless of mold and RBC types) when compared with the 4-mm samples. In contrast, the DeepCure-S 10-mm samples increased by only 13.36%.

Figures 2 to 4 support previous reports that the bulk-fill materials are more transparent compared with a conventional RBC.[39] Also, as expected, more light was transmitted when the white Delrin molds were used compared with the metal molds. Figures 2 to 4 also highlight the differences between the RBCs and show that very little violet light (<420 nm) was transmitted through 6 mm of all three RBCs. The increased absorbance of the violet light below 420 nm from the polywave LCU partly occurs because of the Rayleigh scattering of light, where the filler particles within the RBC tend to scatter more light at the shorter wavelengths.[40] Thus, the power and benefit of the violet light emitted from the polywave LCU will be lost as the thickness of the RBC increases.[31] Of note, the monowave LED curing light used in this study (DeepCure-S) emitted light from 430 to 480 nm, with a peak at 455 nm. Since approximately 50% of the light absorption for Ivocerin still occurs at 440 nm, this monowave LED delivers a functional emission spectrum that overlaps the Ivocerin absorbance range and allows this particular LCU to activate both the Ivocerin and CQ photoinitiators. Consequently, the need to use a polywave curing light to light cure this bulk-filling RBC should be questioned. However, it should be acknowledged that not all monowave LED LCUs will deliver a functional amount of light between 430 to 460 nm.[41]

This *in vitro* study found the greatest light transmission and DOC in Tetric Evoceram Bulk Fill followed by Aura Bulk Fill, and Filtek Supreme Ultra had the least. Of the three RBCs tested, both bulk-fill RBCs achieved a 4-mm DOC when tested in both the 4- and the 10-mm-diameter metal mold as per ISO 4049. In contrast, when the DOC was tested in the 4-mm-diameter metal mold, the conventional material, Filtek Supreme, did not achieve a 4-mm DOC, but it did in the 10-mm-diameter mold. This is to be expected because bulk-fill RBCs use more efficient photoinitiator systems, and by matching the refractive indices of their fillers and matrix, they increase the amount of transmitted light.

This *in vitro* study provides important information for clinicians when curing a deep restoration with a single increment of RBC. The conventional RBC, Filtek Supreme Ultra, was light cured for four times the minimum recommended exposure time (40 seconds instead of 10 seconds), and yet it still had the shallowest DOC. This shows that if the clinician wishes to place a 4-mm increment, the clinician must use a bulk-fill RBC, and they should not just try curing a conventional RBC for a longer time. Second, the DOC will be less in small cavities with narrow openings compared with larger, wider cavities (eg, a mesial occlusal distal restoration in a molar tooth).

The 10-mm internal diameter metal molds used in this study resemble the worst-case clinical condition when restoring a multisurface restoration with a metallic matrix band.[42] The mesial-distal dimensions of MOD cavity preparation in mandibular molar teeth are on average 11 mm in the mesiodistal dimension, 10.5 mm in the buccolingual dimension at the crown, and 9 mm at the cervix.[43] Although both bulk-fill RBCs achieved a 4-mm DOC when tested in the 4- and 10-mm-diameter metal mold as per ISO 4049, the clinician should recognize that the DOC will be less adjacent to the metal matrix band.

The results also show that the 4-mm-diameter metal mold specified in the 2009 ISO 4049 standard will underestimate the DOC, and this 4-mm-diameter mold may not be ideal when testing bulk-fill RBCs that are intended to fill larger cavities. Instead, a mold diameter that is similar to the light tip diameter may be preferable. Since the mold diameter and material significantly affect the DOC of both conventional and bulk-fill RBCs, the reader should pay careful attention to the mold diameter and opacity used in any study.

CONCLUSIONS

Within the limitations of this study, the following was concluded:

1) Of the three RBCs tested, only the bulk-fill products achieved a 4-mm DOC when tested in the 4-mm-diameter metal mold as per ISO 4049.
2) When used for 40 seconds, both the polywave LED curing light and the monowave LED curing light produced the same DOC for the same conditions, however the conventional composite still did not achieve a 4-mm DOC when tested in the 4-mm-diameter metal mold.
3) Increasing the mold diameter from 4 to 10 mm meant that the RBCs received a greater radiant power and resulted in greater DOC values.
4) Greater DOC is achieved in white semitransparent Delrin molds compared with metal molds.
5) All three RBCs achieved a 4-mm DOC when tested in the 10-mm-diameter metal mold.
6) The use of bulk-fill RBCs increased the DOC up to 28% compared with a conventional RBC.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of King Saud University.

Conflict of Interest

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

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