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ORIGINAL ARTICLE

Impact of light-curing distance on the effectiveness of cure of bulk-fill resin-based composites

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Abstract *Objective:* To investigate the effect of light-curing distance on the effectiveness of cure (EC) of bulk-fill resin-based composites (RBCs).

Materials and methods: Two bulk-fill RBCs (a Tetric N-Ceram Bulk Fill (TN) and a Filtek Bulk Fill (FK)) are evaluated. Specimens (4 mm high) are cured for 20 s at different distances (0 mm (D0), 2 mm (D2), 4 mm (D4), 6 mm (D6) and 8 mm (D8)) and stored for 24 h in 100% relative humidity at 37 °C. The top and bottom surface hardness (SH) ($n = 12$) are assessed using a Knoop microhardness tester and the EC is calculated. The EC is characterized by the hardness ratio (HR) (mean bottom: top SH). An HR of 0.8 is used as the benchmark for an effective/adequate cure. Data are analyzed using one-way analysis of variance and Tukey's post hoc test ($\alpha = 0.05$). Correlations between the top and bottom surfaces are examined using the Pearson correlation ($\alpha = 0.05$).

Results: For the TN, the HR at D8 is significantly lower than all other light-curing distances, while for the FK, it is significantly lower than D0 only.

Conclusion: The effect of light-curing distance on the EC of bulk-fill RBCs is material dependent. Notwithstanding the light-curing distance, the EC of the FK and TN is below the threshold HR value of 0.8 when photopolymerized for 20 s in 4 mm increments in black opaque molds.

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1. Introduction

Bulk-fill resin-based composites (RBCs) have been developed with improved depths of cure of up to 4 mm (Jang et al., 2015). This has been achieved by improving material translucency through incorporating large-sized fillers and decreasing the filler load. Some manufacturers have added novel photoinitiators, including germanium derivatives, which have been reported to increase visible light absorption (Moszner et al., 2008).

For optimum properties and clinical longevity, RBC restorations must be photopolymerized at maximum light-curing unit (LCU) radiant exposure under ideal conditions (Price et al., 2004). The light-curing guide (LCG) should be placed perpendicular and as close as possible to the restoration to deliver a homogenous light beam with minimum light attenuation (Konerding et al., 2016). The cusp height of posterior teeth, the use of separation rings or matrices and the shape and/or size of the LCG coupled with limitations in mouth opening make it difficult and sometimes impossible to keep the LCG tip close to the restoration surface.

Furthermore, the average depth of Class II proximal cavities ranges between 4 mm and 7 mm and sometimes is even greater than 8 mm (Hansen and Asmussen, 1997). Increasing the distance between the LCG tip and conventional RBCs intensifies light attenuation and decreases the power density (Meyer et al., 2002), resulting in decreased surface hardness (SH), effectiveness of cure (EC) and degree of conversion of RBCs (Pires et al., 1993; Aguiar et al., 2005).

The effect of light-curing distance on the cure of bulk-fill RBCs is clinically pertinent because they are cured in 4 mm increments making the restoration bottom surface particularly vulnerable to light scattering within the RBCs and light attenuation in air as they are further from the light source. The objective of this study is thus to assess the impact of light-curing distance on the SH and EC of bulk-fill RBCs. The null hypotheses are that the SH and EC of bulk-fill RBCs are not influenced by light-curing distance and that there is no difference in the SH and EC between different bulk-fill RBCs.

2. Materials and methods

2.1. SH testing

Two restorative bulk-fill RBCs, (a Tetric N Ceram Bulk Fill (TN) and a Filtek Bulk Fill (FK)) were selected (Table 1). Customized black Perspex® molds with a 5 mm internal diameter and a 4 mm depth were used for specimen fabrication. A transparent matrix strip (Ruwa Matrix Strips) was positioned at the bottom of the molds. The RBCs were then packed in a single increment. A second transparent matrix strip was placed on top. Excess material was extruded by finger pressure applied with a glass slide. Specimens were irradiated for 20 s through the top matrix strip using a polywave light-emitting diode (LED) LCU (Bluephase N, Ivoclar Vivadent, Schaan, Liechtenstein) in high-intensity mode at different light-curing distances (0 mm (D0), 2 mm (D2), 4 mm (D4), 6 mm (D6) and 8 mm (D8), (n = 12)). For D0, the LCG tip was placed directly against the top matrix strip. For other light-curing distances, the LCG was supported by a metal locating jig rested on supports of different thicknesses (Fig. 1).

The LCU was recharged every 12 specimens and a radiometer (Bluephase Meter II, Ivoclar Vivadent, Schaan, Liechtenstein) was used, ensuring constant radiant emittance (1058 ± 8.40 mW/cm^2) and power (643 ± 2.12 mW). The top and bottom matrix strips were removed after light-curing the specimens and before their storage in a lightproof container at 100% relative humidity and 37 °C for 24 h in an incubator (IN450, Memmert, Schwabach, Germany). Specimens were kept in their molds during storage.

The Knoop hardness number (KHN) was determined with a microhardness testing machine (Shimadzu Corporation, Kyoto, Japan). Three indentations were made on the top and bottom surfaces of each specimen using a 10 g load and

Table 1 Technical profiles provided by the manufacturers of the bulk-fill RBCs evaluated.

Material (Abbreviation)	Manufacturer	Shade	Matrix	Filler Type	Filler Load		Photoinitiator
					wt. %	vol.%	
Tetric N Ceram® (TN)	Ivoclar Vivadent, Inc., NY, USA	IVA	Bis-GMA Bis-EMA UDMA (21 wt% organic matrix in total)	• Prepolymer fillers 17 wt%Barium Aluminum Silicate glass fillerytterbium trifluoridespherical mixed oxide filler	75–77	53–55	• Acyl phosphine oxideCamphorquinoneDibenzoyl germanium derivative (Ivocerin)
Filtek™ Bulk Fill (FK)	3 M, St. Paul, MN, USA	A2	AUDMA UDMA DDDMA	• Silica fillersZirconia fillersZirconia/Silica fillersYtterbium Trifluoride	76.5	58.4	Camphorquinone

Bis-GMA = Bisphenol-A glycidyl methacrylate.
Bis-EMA = Ethoxylated bisphenol-A-glycidyl methacrylate.
UDMA = Urethane Dimethacrylate.
AUDMA = high molecular weight aromatic dimethacrylate.
DDDMA = 1, 12-Dodecanediol dimethacrylate.

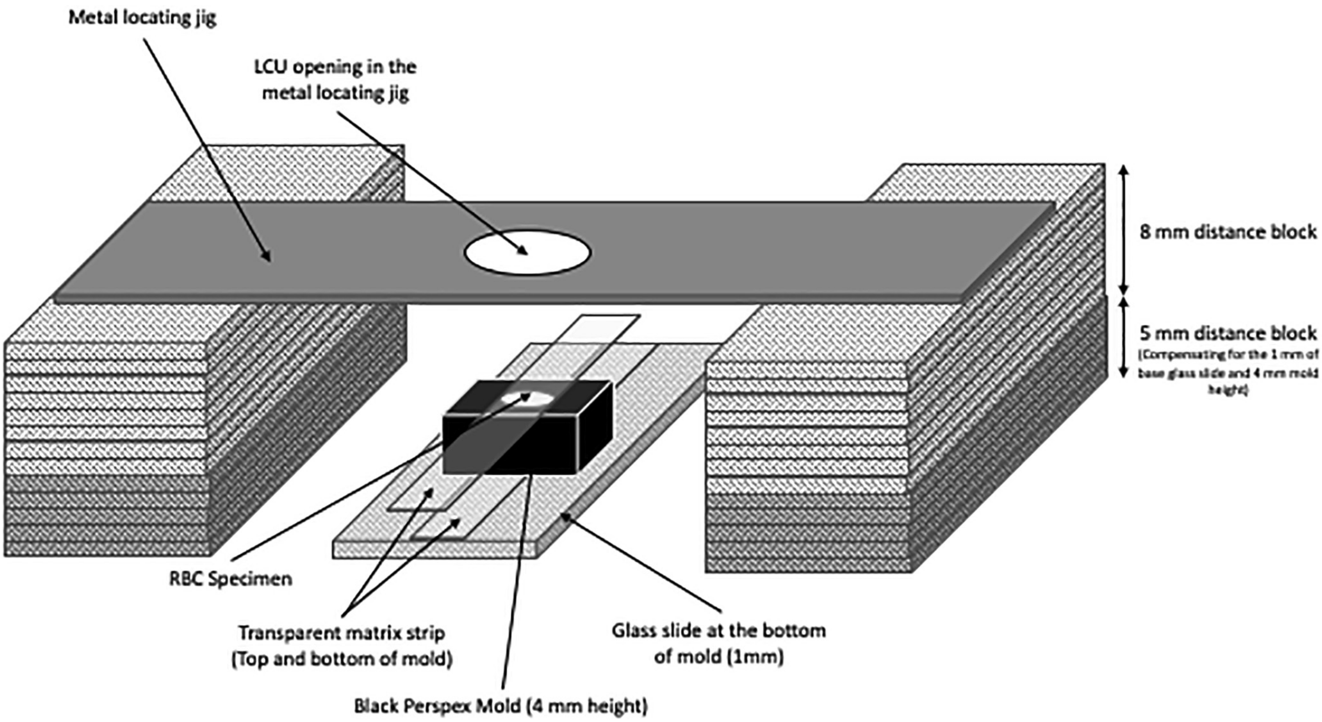

Fig. 1 Schematic diagram showing the experimental setting at 8 mm light-curing distance.

a dwell time of 10 s. The first indentation was made in the center, the second and the third were made 300 µm to its right and left, respectively. The KHN was calculated using:

$$\mathrm{KHN} = 1.451\left(\frac{F}{D^2}\right)$$

where F is the test load in Newtons and D is the indentation longer diagonal length in millimeters. The three readings were averaged for each surface and specimen. The mean top and bottom KHN ($n = 12$) were subsequently computed. The EC was characterized by the mean bottom: top hardness ratio (HR).

2.2. Statistical analysis

SPSS version 23.0 (SPSS Inc, Chicago, USA) was used to analyze the data. Normality testing was performed using the Shapiro-Wilk test. As the data were found to be normally distributed, one-way analysis of variance ($p < 0.05$) and Tukey's post hoc test ($\alpha = 0.05$) were used to compare the KHN and HR between different light-curing distances for each RBC. Material comparisons were made using an independent sample T-test. Correlations between the top and bottom surfaces were computed using the Pearson correlation ($\alpha = 0.05$).

3. Results

Tables 2 and 3 show different KHN and HR mean values and data. Significant differences in the top and bottom KHN were observed between the various light-curing distances. The ranking of the HR was generally similar for the two bulk-fill RBCs except for light-curing at D2 and D4. For the TN, light-curing at D8 resulted in a significantly lower HR when compared to

Table 2 Mean top and bottom Knoop hardness number (KHN) and hardness ratios (HR) for the TN and FK.

Curing Distance (mm)	Top KHN (SD)	Bottom KHN (SD)	Hardness Ratio (SD)
Tetric N Ceram® (TN)			
D0	35.44 (3.60)	16.39 (1.77)	0.46 (0.05)
D2	41.24 (3.05)	17.56 (3.65)	0.43 (0.09)
D4	38.13 (5.33)	16.89 (1.35)	0.45 (0.08)
D6	38.50 (2.11)	14.15 (1.51)	0.37 (0.05)
D8	34.54 (2.89)	9.12 (1.14)	0.27 (0.04)
Filtek™ Bulk Fill (FK)			
D0	44.76 (1.68)	35.41 (4.69)	0.79 (0.11)
D2	50.07 (2.61)	37.48 (3.73)	0.75 (0.07)
D4	51.12 (2.85)	37.60 (3.09)	0.74 (0.08)
D6	46.67 (3.18)	34.14 (3.01)	0.73 (0.08)
D8	48.17 (4.48)	32.57 (3.19)	0.68 (0.07)

Table 3 Ranking and comparison of the SH and HR between the different light-curing distances for the TN and FK.

Materials	TN		FK	
	Ranking	**Results***	**Ranking**	**Results***
Top KHN	D2 > D4 > D6 > D0 > D8	D2 > D0, D8	D4 > D2 > D8 > D6 > D0	D2, D4, D8 > D0 D2, D4 > D6
Bottom KHN	D2 > D4 > D0 > D6 > D8	D2, D4 > D6 D0, D2, D4, D6 > D8	D4 > D2 > D0 > D6 > D8	D2, D4 > D8
HR	D0 > D4 > D2 > D6 > D8	D0, D4 > D6 D0, D2, D4, D6 > D8	D0 > D2 > D4 > D6 > D8	D0 > D8

Abbreviations: SH, Surface hardness; TN, Tetric N-Ceram Bulk Fill; FK, Filtek™ Bulk Fill.
* Indicates statistically significant differences between curing distances at $p < 0.05$ (Results of one-way analysis of variance and Tukey post-hoc tests).

Table 4 Comparison of the SH and HR between the TN and FK at the different light-curing distances.

Curing distance	Top KHN	Bottom KHN	HR
D0	FK > TN	FK > TN	FK > TN
D2	FK > TN	FK > TN	FK > TN
D4	FK > TN	FK > TN	FK > TN
D6	FK > TN	FK > TN	FK > TN
D8	FK > TN	FK > TN	FK > TN

> denotes statistically significant differences between materials at $p < 0.05$ (Results of independent sample *T*-test).

other light-curing distances. In addition, the HR at D6 was significantly lower than that at D0 and D4. For the FK, significant differences in the HR were observed only between light-curing at D0 and D8.

Table 4 presents a comparison of the SH and HR between the TN and FK. For all light-curing distances, the top KHN, bottom KHN, and HR of the FK were significantly greater than for the TN. A weak and positive correlation between the top and bottom KHN values was noted for both the TN and FK ($r = 0.37$ and 0.28, respectively).

4. Discussion

This study examined the influence of light-curing distance on the SH and EC of bulk-fill RBCs. The SH and EC were impacted by light-curing distance, and significant differences between materials were observed. Therefore, both null hypotheses were rejected. The effect of light-curing distance on the EC of bulk-fill RCBs was material dependent. Based on an HR of 0.8 for an effective/adequate cure (Yap et al., 2016), the TN could not be satisfactorily cured regardless of light-curing distance, while the FK could be amply cured up to a distance of 6 mm, taking into account a 10% variance.

The EC describes the extent of the polymerization reaction of RBCs, dictating many of their physical and mechanical properties (Yap and Seneviratne, 2001). The EC of RBCs can be assessed directly by obtaining the degree of conversion using Fourier transform infrared spectroscopy or indirectly by determining the HR. Knoop microhardness testing was selected for assessing the HR due to its strong correlation to the degree of conversion (Asmussen, 1982), technical simplicity, and efficiency. A pilot study was performed using different microindentation loads/dwell times and it was ascertained that a 10 g load for 10 s allowed for indentation borders to be confined within the microscope's field of view.

Different light-curing distances were used to simulate various clinical conditions with D8 representing the worst-case scenario. Black Perspex® molds were used with a black background to ensure color standardization around the specimens and to avoid unwanted light absorption or reflection. White Delrin® molds result in a greater depth of cure (AlShaafi et al., 2018), while stainless-steel ones absorb more light than black colored molds. Hence, black Perspex® molds were chosen to test extreme conditions, giving more reliable comparisons between various products (Harrington and Wilson, 1993; Erickson and Barkmeier, 2017).

Although the oxygen-inhibition layer cannot be completely prevented during specimen preparation, the matrix strips used minimized its formation and produced flat and smooth surfaces that are required for microhardness testing. Polishing was avoided to prevent heat generation that affects polymerization (Chinelatti et al., 2006). Additionally, the SH is independent of the specimen surface finish as the indenter penetration was reported to be sufficiently deep (Chung & Yap, 2005).

The TN specimens were cured for 20 s despite the manufacturer recommendation of 10 s, as this shorter period resulted in specimens that were too soft for Knoop microindentation. To ensure maximum radiant exposure, the LCU was fully charged after every 12 specimens. Low battery levels decrease the LED LCU intensity (Tongtaksin and Leevailoj, 2017), which can influence some RBCs properties (Pereira et al., 2016). Due to the light beam inhomogeneity (Price et al., 2010), all samples were cured while maintaining the LCU in the same orientation. The molds were marked accordingly to ensure specimen placement within the same orientation on the microindenter.

A general decrease in the EC was observed with increasing light-curing distance. This could be explained by the reduction in the irradiance received by the specimens as the distance increases (Price et al., 2000; Corciolani et al., 2008; Meyer et al., 2002). Another possible explanation is the use of high-power polywave LCU which results in a lower HR when compared to a monowave LCU (Gan et al., 2018). These results are consistent with findings for conventional RBCs (Pires et al., 1993; Rode et al., 2007; Vandewalle et al., 2005; Thome et al., 2007) and bulk-fill RBCs (Malik and Baban, 2014).

For both bulk-fill RBCs, the highest HR was achieved when the materials were cured at D0. A 41.3% reduction in HR was observed when the TN was cured at D8. The very low HR attained (0.27) may lead to mechanical and biological complications in-vivo. The performance of the FK was significantly better. Light curing at D8 resulted in a 13.9% drop in the HR. In addition, regardless of the light-curing distance, the top and bottom KHN and HR of the TN were significantly lower than for the FK. The effect of light-curing distance on the EC was therefore material dependent. This accounts for the disparity in the EC of bulk-fill RBCs reported in the literature with some indicating HRs above 0.8 and others describing values below this threshold (Malik and Baban, 2014; Flury et al., 2012; Garcia et al., 2014; Alrahlah et al., 2014).

The overall lower performance of the TN compared to the FK may be attributed to differences in translucency, photoinitiators and filler loading. The shade used for the FK was A2, while that for the TN was IVA, which is a universal shade corresponding to shades A2 and A3. Furthermore, the TN incorporates Ivocerin® as a photoinitiator, which results in slightly higher opacity compared to other bulk-fill materials (Peschke, 2013). The TN utilizes both CQ and Ivocerin®, while the FK uses only CQ as its photoinitiator. Ivocerin® is unable to fully compensate for the lower translucency of the TN.

A higher CQ content has been shown to yield greater light transmission and higher levels of conversion (Howard et al., 2010). The relatively higher proportion of CQ in the FK could explain its greater SH at all light-curing distances. Moreover, the filler volume fraction for the FK was higher than that of the TN. Lower filler volumes have been directly associated with lower KHN (Chung and Greener, 1990). The hardness of an RBC is affected by the filler content, its distribution and its size. The TN has prepolymerized small-sized filler particles that contain a considerable resin phase. This may have contributed to its overall lower SH values.

LCU-related factors may have also contributed to the significantly lower TN values when compared to the FK. Less violet light (<410 nm) was reported to reach the bottom of the TN when compared to the FK (Shimokawa et al., 2018). The shorter violet spectrum wavelengths were unable to penetrate RBCs as deeply as the longer blue spectrum wavelengths, with only CQ being excited (Lima et al., 2018) regardless of the uniformity of the wavelength distribution of the beam emissions (de Oliveira et al., 2019).

The highest top and bottom KHN were anticipated when the RBCs were cured at D0. They were, however, achieved when cured at D2 and D4 for the TN and FK, respectively. Modern polywave LED LCUs, like the Bluephase N, employ multiple LED chipsets that make light bundling more difficult, resulting in an inhomogeneous beam profile and non-uniform radiant emittance distribution across their LCG (Price et al., 2010). This is compounded by the positioning of the LCG and the material depth (Michaud et al., 2014). The polymerization reaction is a diffusion-controlled response (Anseth et al., 1994). When the RBCs are cured at D0, a rapid increase in material viscosity may limit the diffusion rate of growing chains, leading to less cross-linking and lower microhardness. This phenomenon is akin to that observed in earlier studies where the maximum microhardness was achieved not at the top but 0.2–2 mm below the cured RBC surface (Flury et al., 2012; Ilie et al., 2013). Collectively, the aforementioned factors may partially explain the unexpected SH findings.

The KHN at the top surface was less affected by the light-curing distance and was a poor indicator of the bottom KHN. The correlation between the top and bottom KHN was weak ($r = 0.37$ and 0.28 for the TN and FK, respectively). This was consistent with similar study results on conventional RBCs (Pires et al., 1993). At all light-curing distances, the top KHN was substantially higher than the bottom KHN as with conventional materials (Sobrinho et al., 2000; Pires et al., 1993; Aguiar et al., 2005), and other bulk-fill RBCs (Malik and Baban, 2014; Farahat et al., 2016). This may be attributed to light scattering and absorption through the 4 mm thick specimens (Musanje and Darvell, 2006). The RBC shade, filler size and distribution affect the amount of light transmission and hence the EC (Guiraldo et al., 2009; Jeong et al., 2009).

The present study has some limitations. First, only two bulk-fill RBCs and one LCU were evaluated. Future studies should incorporate more products as bulk-fill RBCs are not a homogeneous class of materials. Flowable bulk-fill materials should also be assessed. A critical light-curing distance should be derived for individual products. Second, EC could be supplemented with Fourier transform infrared spectroscopy and other direct techniques. Lastly, photopolymerization of bulk-fill RBCs is a complex phenomenon. In addition to LCG positioning, a combination of many other factors, including the LCU type, light beam profile/distribution, as well as RBC photoinitiator, filler type/size/volume, translucency, and depth may be involved.

5. Conclusions

Within the limitations of this study, the following conclusions can be made:

1. For both bulk-fill RBCs, a general decrease in the EC was observed with increasing light-curing distance. LCUs should not be placed more than 4 mm away from the surface of the bulk-fill RBC.
2. Notwithstanding light-curing distance, even when using a 20 s exposure, the EC of the FK and TN was below the threshold HR of 0.8 when photopolymerized in 4 mm increments in opaque black molds.
3. As the impact of light-curing distance on the EC of the bulk-fill RBCs is material dependent, additional research is required on a wide range of contemporary bulk-fill materials. The critical light-curing distance should be determined.

Ethical Statement

Our research has been approved by the ethical committee of the Faculty of Dentistry Medical Ethics Committee (FDMEC) at University of Malaya.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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