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The Effect of Different Light-curing Units and Tip Distances on the Polymerization Efficiency of Bulk-fill Materials

HNA Al Nahedh • DF Al-Senan • AS Alayad

Clinical Relevance

Clinicians should exercise caution when selecting and placing resin-based bulk-filling materials using light-curing units for the restoration of deep cavities. Increased distance from the light tip has a detrimental effect on the mechanical properties of composite resin materials.

SUMMARY

Problem Statement: In an average class II posterior preparation, the curing light tip is placed at a distance from the restoration surface that far exceeds the 1-mm manufacturer's recommendation. This distance can have potentially detrimental effects on the curing efficiency of the light-curing unit as well as the properties of the resin-based composite restoration, especially at the bottom of the cavity preparation.

*Hend N A Al Nahedh, BDS, MSD, College of Dentistry, Department of Restorative Dental Sciences, King Saud University, Riyadh, Saudi Arabia

Dana F Al-Senan, BDS, MSD, College of Dentistry, Clinical Dental Sciences Department, Princess Nourah University, Riyadh, Saudi Arabia

Abdullah S Alayad, BDS, CAGS, MSD, DScD, College of Dentistry, Department of Restorative Dental Sciences, King Saud University, Riyadh, Saudi Arabia

*Corresponding author: PO Box 60169 Riyadh 11545, Kingdom of Saudi Arabia; email: h_nahed@yahoo.com

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Purpose: The purpose of this study was to evaluate the effects of various types of light-curing units (LCUs) and the different curing distances on the degree of conversion (DC) and the surface hardness of bulk-fill composite materials.

Methods and Materials: A total of 390 specimens of three resin-based composites (RBCs) were fabricated. Two bulk-fill RBCs, including Filtek Bulk Fill Posterior (3M ESPE GmbH, Seefeld, Germany) and Tetric N-Ceram Bulk Fill (Ivoclar Vivadent AG, Schaan, Liechtenstein), as well as a Filtek Z350 XT nano-filled composite (3M ESPE GmbH, Seefeld, Germany), were utilized. In this study, the Vickers microhardness number (VMN) and the DC were evaluated at 2 and 4 mm thicknesses. Polymerization for 20 seconds was performed using two high-power light-curing units, namely the polywave Bluephase G2 light-emitting diode (LED) LCU (Ivoclar Vivadent AG, Schaan, Liechtenstein) and the monowave Elipar Deep Cure S LED LCU (3M Oral Care, St Paul, MN, USA) at 0, 2, and 4 mm distance between the

curing tip and the RBC surface. The results were analyzed using the two-way analysis of variance method. Scheffe's post-hoc multiple comparison tests were used to determine significant differences between the materials, the LCU, and the tip distances.

Results: The highest DC (70.17) was shown by Filtek Bulk Fill Posterior at a distance of 0 mm, whereas the lowest DC (45.99) was measured for the conventional Filtek Z350 XT at a 4 mm distance. Moreover, higher VMNs were shown by Filtek Bulk Fill and Filtek Z350 composites at 0 mm distance than by the Tetric N-Ceram Bulk Fill composite material when cured with a Bluephase G2 LCU. For all materials, a significant decrease in the DC and mean VMN values was observed at a 4 mm distance in comparison with 0 and 2 mm distances.

Conclusions: The DC and VMN values among the studied bulk fill materials were more significantly affected by the material composition and curing protocols. The increased distance from the light tip has a detrimental effect on the mechanical properties of composite resin materials. Significant differences were observed in the curing efficiency of the two LCUs investigated.

INTRODUCTION

With the development of dental materials, instruments, and clinical techniques, resin-based composites (RBCs) have become the most commonly used materials for direct restoration to satisfy the demands of patients for aesthetics and functional restorative treatment.[1] One of the major problems with RBCs is polymerization shrinkage which generates stress at the tooth restoration interface, resulting in debonding when the bond strength is exceeded by the shrinkage stress.[2] To minimize stress from polymerization shrinkage as well as to acquire adequate mechanical properties for the composite, an incremental placement technique is needed in which the composite is layered and cured in 2-mm increments.[3] However, the technique is quite time-consuming,[4] and if not performed properly, can result in void incorporation in the bulk and at the margins of the restoration, potentially leading to the weakening of the restoration or microleakage.[5] Lately, bulk-fill composites have been developed to simplify the composite resin placement technique. Manufacturers claim that bulk-fill composites create a lower polymerization shrinkage stress and have higher light transmission properties due to a reduction of light scattering at the filler matrix interface by either increasing the scope of the filler or decreasing the quantity of the fillers. Therefore, bulk-fill composites can be used for layers with up to 4-5 mm thickness.[4] Several bulk-fill RBCs are now available, some of which are flowable (low viscosity), whereas some of them are characterized with higher viscosity. High-viscosity bulk-fill RBCs do not require an additional surface layer of conventional hybrid RBC and that they can be used as a single-step bulk-filling material.[6]

Light-curing units (LCUs) play an important role in the development of the basic properties of RBCs. Quartz-tungsten-halogen units have been widely used for the polymerization of RBCs for decades.[7-9] However, they are now largely replaced by light-emitting diode (LED) units. Most of the currently used LED LCUs are second-generational with a single high-powered diode. The improvement of the diode technology allowed an increase in the irradiance of the unit and, accordingly, a decrease in the recommended irradiation time.[10]

There are two main types of LCUs available currently, mono- and polywave LED units. The narrow spectrum of monowave LED LCUs may hinder their ability to optimally cure bulk-fill composites with multiple photoinitiators with varying peak absorption ranges. However, polywave LED LCUs (third-generational) can radiate different wavelengths of light to polymerize different photoinitiators.[11]

During the curing process, some of the light is reflected off the surface of the RBC, and some light that passes through the RBC is absorbed or scattered based on the particle size of the fillers as well as the refractive indices of the resin matrix and the fillers. Consequently, the intensity of the light is decreased and its effectiveness is reduced as the depth increases.[12] Meanwhile, the composition as well as the initiator systems of the bulk-fills are comparable to those of the conventional RBCs.[13]

Light intensity diminishes when the distance from the tip of the light source to the resin composite is increased. Therefore, the most common clinical recommendation for the position of the tip is 1 mm from the resin.[14]

A previous study evaluated the impact of the distance between the light guide tip of the curing unit and material surface on the DC and Knoop microhardness of a composite resin. Their results showed that increased curing distance can affect the mechanical properties of composite restoration.[15] Another study has also shown that greater tip distances produce a decrease in microhardness and DC values.[16] However, a similar correlation was not performed for bulk-fill RBCs.

The purpose of the present study was to evaluate the effects of different LCU types as well as the distance from the LCU tip on the DC and the surface microhardness of bulk-fill composite materials.

The null hypotheses of this study were that there would be no significant differences in the DC of two bulk-fill composites after polymerization with different LCUs, no differences in using different distances between the LCU tips and the restoration surface on curing parameters and surface hardness, and no differences in surface hardness with the application of different LCUs.

METHODS AND MATERIALS

Three-hundred and ninety specimens of two bulk-fill resin composites (Filtek Bulk Fill Posterior, shade A2 [3M ESPE; St Paul, MN], Tetric N-Ceram Bulk Fill [universal A shade; Ivoclar Vivadent; Schaan, Liechtenstein], and Filtek Z350 XT conventional nano-filled composite resin [shade A2; 3M ESPE]) were used in this study (Table 1). The microhardness and the DCs were evaluated at 2- and 4-mm thicknesses after polymerization using two LCUs, including polywave Bluephase G2 LED LCU (Ivoclar Vivadent) and monowave LED LCU (3M ESPE). The light-curing tip was positioned at distances of 0, 2, and 4 mm from the surface of the composite material. The curing time was 20 seconds for the two LCUs.

Specimen Preparation

Disk-shaped specimens were fabricated from the two bulk-fill materials to be used in hardness measurements (n=120). A special custom sectional Teflon mold (10 mm in diameter and 4 mm deep) was used, the uncured paste of each composite was placed in two layers, each of which was 2 mm thick and the layers were separated by a celluloid strip. Sixty specimens for each material were fabricated using either Bluephase G2LCU or Elipar DeepCure-S (n=30) at 0, 2, and 4 mm distance (n=10). The distance from the composite surface was calibrated and stabilized using a laboratory ring and clamp stand (Dentalfarm; Torino, Italy). Vickers microhardness was measured on both sides of each layer of these discs.

For evaluation of the degree of conversion, rectangular specimens (n=120) were fabricated from the two composite materials (n=60) using a custom Teflon mold (6 mm in length, 3 mm in width, and 4 mm in depth). The materials were placed in the mold over a glass slab. After insertion into the mold, a glass plate of 1.00 mm thickness was secured over the mold to

Table 1: *Resin Composite Materials Used in the Study*

Materials/Shade	Lot Number	Material Type	Resin Matrix	Filler
Tetric N-Ceram Bulk Fill (Ivoclar-Vivadent, Liechtenstein) Shade IVB The European trade name Tetric EvoCeram Bulk-Fill	T47219	Packable hybrid bulk-fill composite	Bis-GMA, Bis-EMA, and UDMA	Barium glass, prepolymer, ytterbium trifluoride, and mixed oxide. Inorganic filler particle size is between 0.04 µm and 3 µm, mean particle size is 0.6 µm Filler loading 75-77% by wt, 53-55% by volume.
Filtek Bulk Fill Posterior Restorative (3M ESPE, USA) Shade A2	N682081	Packable nanofilled bulk-fill composite	ERGP-DMA, diurethane-DMA, and 1, 12-dodecane-DMA	Non-agglomerated/non-aggregated 20-nm silica filler, 4-11-nm zirconia filler, aggregated zirconia/silica cluster filler, and ytterbium trifluoride filler agglomerate 100 nm particles. Filler loading 76.5% by wt, 58.4% by volume
Filtek Z350 XT (3M ESPE, USA) A2 Body shade Trade name in North America Filtek Supreme Ultra	N677462	Nanohybrid composite	Bis-GMA, UDMA, TEGDMA, PEGDMA, and Bis-EMA	Non-agglomerated/non-aggregated 20-nm silica filler, 4-11-nm zirconia filler, and aggregated zirconia/silica cluster filler. Filler loading 78.5% by wt, 63.3% by volume

Abbreviations: UDMA, urethane dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; Bis-EMA, ethoxylated bisphenol-A dimethacrylate; ERGP-DMA, ERGP- dimethacrylate; PEGDMA, Polyethylene glycol dimethacrylate.

flatten the surface. Specimens were divided according to the type of applied LCU into 2 groups (n=30) and afterward subdivided according to tip distances into 3 groups (n=10). The LCU tip was placed at a 0, 2, and 4 mm distance from the top surface of the specimen and subsequently cured for 20 seconds. For each tip distance group, DC measurements were performed (n=10).

Conventional Filtek Z350 XT (3M ESPE) was used as control. Disk-shaped specimens were fabricated to be used in hardness measurements (n=60) using a Teflon mold (10 mm in diameter and 2-mm deep), the specimens were divided into two groups according to the type of LCU (n=30) and subsequently subdivided based on the distances from the LCU tip into three groups (n=10). The DC specimens (n=60) were 6 mm long, 3 mm wide, and 2 mm deep and were cured for 20 seconds at 0, 2, and 4 mm distances. For each LCU and distance subgroup, 10 specimens were fabricated.

Thirty uncured specimens of the three composite materials were placed over the ATR crystal (n=10), and the spectrum of the uncured material was recorded for the duration of one scan.

The analysis and measurement of the irradiance values, spectral emission, and radiant exposure delivered to each specimen at 0, 2, and 4 mm distances were performed using a MARC-RC device (BlueLight Analytics; Halifax, Canada), as shown in Figure 1.

Microhardness Measurement (VMN)

Microhardness was measured using a Vickers hardness tester immediately after the fabrication of the specimen (InnovaTest Europe BV; Maastricht, the Netherlands). The surface of each specimen was subsequently divided into thirds. Three indentations were introduced, one in the center of each third using a Vickers microhardness indenter with 300g load applied for 15 seconds. Measurements were performed on the top surface of the top layer, the bottom surface of the top layer, the top surface of the bottom layer, and the bottom surface of the bottom layer. Afterward, the mean microhardness (VMN) values were calculated for each surface.

Bottom-to-top surface hardness ratios were calculated separately for the top and bottom layers and the full thickness (bottom surface at 4 mm depth/top surface hardness).

Degree of Conversion Measurement

The DC measurements were performed from the uncured material immediately after removal from the syringe, and the irradiated specimen surface within 2 hours of curing. After photoactivation, absorbance peaks were obtained through the transmission mode of a Fourier-transform infrared spectrometer (FTIR, Nicolet iS10 Series; Thermo Scientific, Waltham, MA). The excitation was an Nd:YAG (neodymium-doped yttrium aluminum garnet) laser at 1038 nm with a laser power of 800 mW and a resolution of 4 cm^{-1}. The spectra of the uncured composites were recorded in the same manner.

DC calculations were performed by comparing the relative change of the band at 1638 cm^{-1} representing the aliphatic C=C stretching mode to the aromatic C=C band at 1608 cm^{-1}, before and after polymerization. The integrated intensities of the aliphatic and aromatic C=C bands were used for the DC calculation based on the following equation:

$$DC\ (\%) = 1 - R_{polymerized}/R_{unpolymerized},$$

where R = (aliphatic C=C band area)/(aromatic C=C band area).

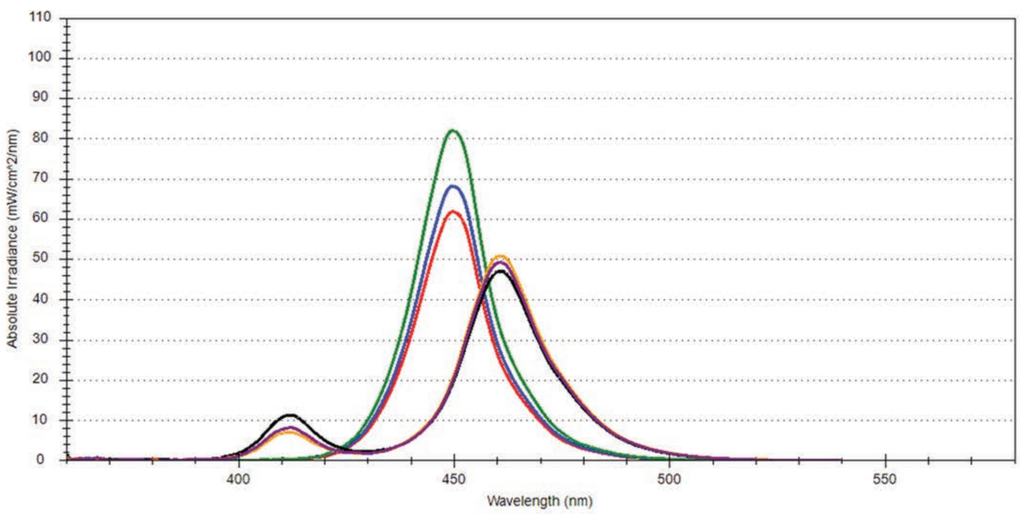

Figure 1. *Spectrum emission for Blue Phase G2 and Deep Cure S at 0, 2, and 4 mm distances for 20 seconds. The short lines on the right refer to Blue Phase G2 and the longer lines on the left refer to Deep Cure S.*

Statistical Analyses

Data were statistically analyzed using SPSS (Statistical Package for the Social Sciences) version 22 for Windows (IBM, Armonk, NY) and the Shapiro–Wilk test was applied for normality testing. Moreover, the homogeneity of variance was analyzed by the Levene's test. Data were presented as means and standard deviation (SD). Due to the detected heterogeneity of variance between the different groups of composites, the two-way analysis of variance (ANOVA) method followed by the one-way ANOVA was used. Scheffe's post-hoc multiple comparison tests were used for the determination of significant differences between the materials, LCUs, and tip distances. Furthermore, multiple regression analyses for the DCs were also carried out at the three locations (top, middle, and bottom). The results were analyzed assuming a significance level of 0.05, at which the statistical power was satisfactory (80%) for the detection of medium-size effects (Cohen's f=0.25).

RESULTS

Microhardness (VMN)

The two-way ANOVA results confirmed that the material, LCU type, and different light tip distances had significant effects on the mean VMN results ($p<0.05$). However, the interaction between the material and the different light tip distances as well as between the curing type and the different light tip distances had no significant effect on the mean VMN results ($p>0.05$).

Top Layer—The bulk-fill materials differed significantly in their VMN ratios (Table 2). The highest microhardness at 0 mm and mean MH ratio (0.984±0.005) were shown by the Filtek Bulk Fill Posterior when cured with the Bluephase G2 LCU, while the lowest mean MH at 4 mm was shown by the Tetric N-Ceram Bulk Fill with DeepCure-S LCU (0.921±0.002). Moreover, the Filtek Bulk Fill Posterior was observed to have higher microhardness values in comparison with the Tetric N-Ceram Bulk Fill at all distances except when cured with the Bluephase G2 LCU at 4 mm (Figure 2). Both materials showed lower microhardness ratios when cured with the DeepCure-S LCU in comparison with the Bluephase G2 LCU.

Significant differences were observed between the three tip distances with all material LCU combinations except for the Tetric N-Ceram Bulk Fill cured with the Bluephase G2 where no significant differences were found between 2 and 4 mm LCU distances.

Bottom Layer—The highest mean VMN (0.837±0.003) was shown by the Filtek Bulk Fill Posterior composite (DeepCure-S, 0 mm), whereas the lowest mean VMN (0.608±0.005) was measured in association with the Tetric N-Ceram Bulk Fill (DeepCure-S, 4 mm).

The Filtek Bulk Fill Posterior composite cured with the Bluephase G2 LCU at 0 mm showed a significantly higher microhardness in comparison with the Tetric N-Ceram Bulk Fill composite material. Furthermore, Tetric N-Ceram Bulk Fill cured with the DeepCure-S

Table 2: *Results of Two-way ANOVA Showing Mean (± SD) VMN Ratios for the Top Layer and Significant Differences Between the Three Distances for Each Material and LCU Combination*

Material	Curing Type	Light Tip Distance (mm)	Mean[a]	Standard Deviation	Df	Mean Square	F	Sig
Tetric N-Ceram Bulk Fill	Blue Phase G2	0	0.980 a	0.004	2	0.001	65.90	0.000
		2	0.967 b	0.002				
		4	0.964 b	0.003				
	Deep Cure S	0	0.941 a	0.004	2	0.001	60.95	0.000
		2	0.930 b	0.006				
		4	0.920 c	0.002				
Filtek Bulk Fill	Blue Phase G2	0	0.984 a	0.005	2	0.006	56.03	0.000
		2	0.969 b	0.002				
		4	0.936 c	0.017				
	Deep Cure S	0	0.97 2a	0.002	2	0.008	862.86	0.000
		2	0.968 b	0.002				
		4	0.921 c	0.004				

[a] *Lowercase letters show the differences within distances for each material and light-curing unit.*

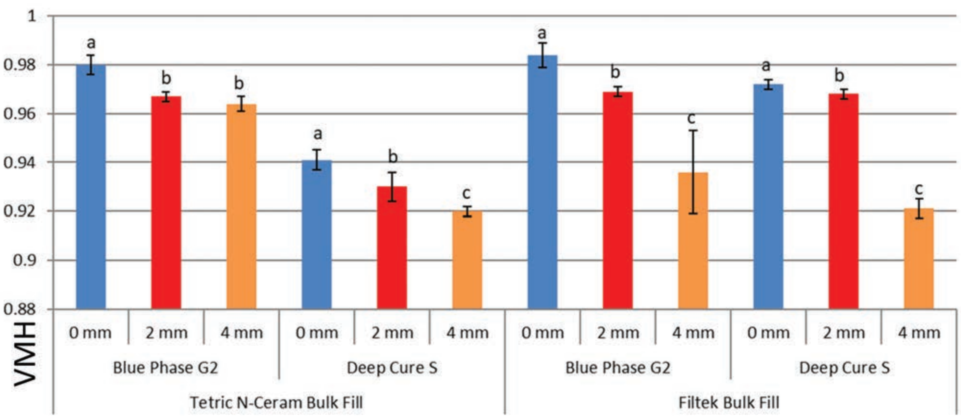

Figure 2. *Bar chart of mean (± SD) microhardness (VMH) ratios for the top surface. Lowercase superscript letters show differences within distances for each material and light curing unit.*

LCU at 4 mm displayed the lowest microhardness ratio. Moreover, microhardness values were found to be higher for both bulk-fill materials when cured with the Bluephase G2 LCU compared to the DeepCure-S LCU (Figure 3). There were significant differences among all three LCU tip distances for Tetric N-Ceram cured with Bluephase G2 and DeepCure-S, however, the Filtek Bulk Fill Posterior showed significant difference with DeepCure-S but not with Bluephase G2 (Table 3).

Full Thickness— The highest mean VMN (0.969±0.008) was attributed to the Filtek Z350 (Bluephase G2, 0 mm), whereas the lowest mean VMN (0.618±0.005) was observed in association with the Tetric N-Ceram Bulk Fill (Bluephase G2, 4 mm) (Figure 4, Table 4). In addition, there was no significant difference measured for the ratio of top to bottom surface microhardness values among the Filtek Bulk Fill and the Filtek Z350 nanohybrid composites at 0 mm distance when cured with Bluephase G2 LCU. Both of them were found to have significantly higher microhardness ratios than the Tetric N-Ceram Bulk Fill composite material, which showed lower microhardness values at 4 mm distance when cured with Bluephase G2 LCU than the former two composites. Besides, all distances revealed significant differences except for the Filtek Bulk Fill Posterior when cured with Bluephase G2.

Multiple regression was performed to predict MH for the material, the curing type, and the distance of the light cure tip. These variables predicted the MH with statistical significance, F (3,146) = 177.753, $p < 0.0005$, $R2 = 0.785$. All three variables added significantly to the prediction, $p < 0.0005$ (Table 5).

Degree of Conversion (DC)

Results of the two-way ANOVA showed that the material, LCU type, light tip distance, and the interaction between the three variables for all three locations (top, middle, and bottom) had significant effects on the mean DC ($p<0.001$) (Table 6). The results of the Scheffe's post-hoc tests of the mean differences in the DC between the variables were significant (Table 7). In addition, all materials showed a higher DC when cured at 0 mm distance in comparison with that at 2 and 4 mm as well as a significantly higher DC at the

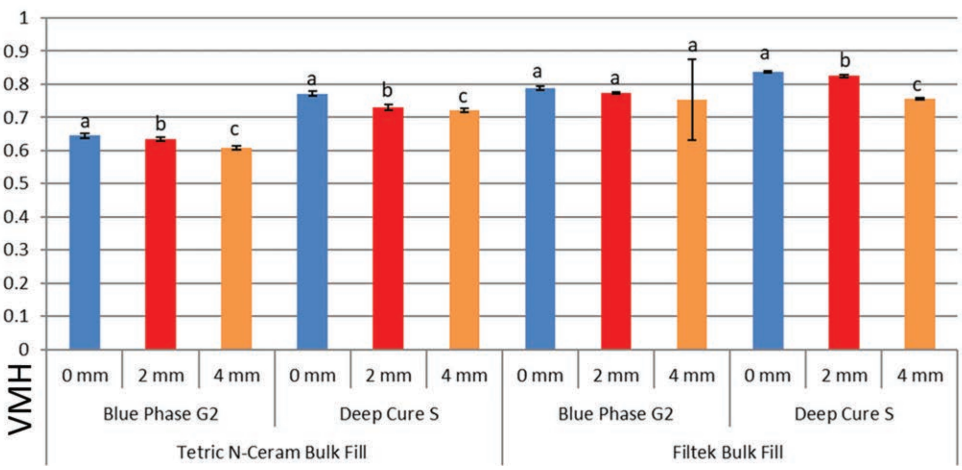

Figure 3. *Bar chart of mean (± SD) microhardness (VMH) ratios for the bottom surface. Lowercase superscript letters show differences within distances for each material and light curing unit.*

Table 3: *Results of Two-way ANOVA Showing Mean (± SD) VMN Ratios for the Bottom Layer and the Significant Differences Between the Three Distances for Each Material and LCU Combination*

Material	Curing Type	Light Tip Distance (mm)	Mean[a]	Standard Deviation	Df	Mean Square	F	Sig
Tetric N-Ceram Bulk Fill	Blue Phase G2	0	0.645 a	0.008	2	0.004	97.93	0.000
		2	0.634 b	0.005				
		4	0.608 c	0.005				
	Deep Cure S	0	0.772 a	0.006	2	0.007	150.22	0.000
		2	0.731 b	0.009				
		4	0.721 c	0.005				
Filtek Bulk Fill	Blue Phase G2	0	0.787 a	0.006	2	0.003	.539	0.589
		2	0.773 a	0.003				
		4	0.754 a	0.122				
	Deep Cure S	0	0.837 a	0.003	2	0.019	2158.54	0.000
		2	0.825 b	0.004				
		4	0.756 c	0.002				

[a] *Lowercase letters show the differences within distances for each material and light-curing unit.*

top surface than the middle or bottom surfaces. The examination of the percentage reduction in the DC values across the different LC tip distances and within each distance indicated that the worst performance was in connection with the DeepCure-S at 4 mm LC tip distance (Table 6).

Top—The highest mean DC (70.17±0.37) was measured with the Filtek Bulk Fill Posterior (Bluephase G2, 0 mm), whereas the lowest (45.99±0.46) was observed with the Filtek Z350 (DeepCure-S, 4 mm) (Figure 5).

Middle (2-mm Thickness)—The highest mean DC (68.90±0.450) was found with the application of the Filtek Bulk Fill Posterior (Bluephase G2, 0 mm), whereas the least (47.54±0.168) was obtained with the Tetric N-Ceram Bulk Fill (DeepCure-S, 4 mm) (Figure 6).

The Filtek Bulk Fill Posterior cured at 0 mm showed a significantly higher DC than both the Tetric N-Ceram and the Filtek Z350 XT when cured with the Bluephase G2 LCU. Also, the Tetric N-Ceram Bulk Fill and the Filtek Z350 XT revealed significantly higher DCs at 0 mm in comparison with those at 2 and 4 mm. All three materials showed significantly higher DCs when cured with the Bluephase G2 LCU compared to the DeepCure-S LCU ($p<0.05$).

Bottom—The highest mean DC (65.56±0.21) was found with the Filtek Bulk Fill Posterior (Bluephase G2,

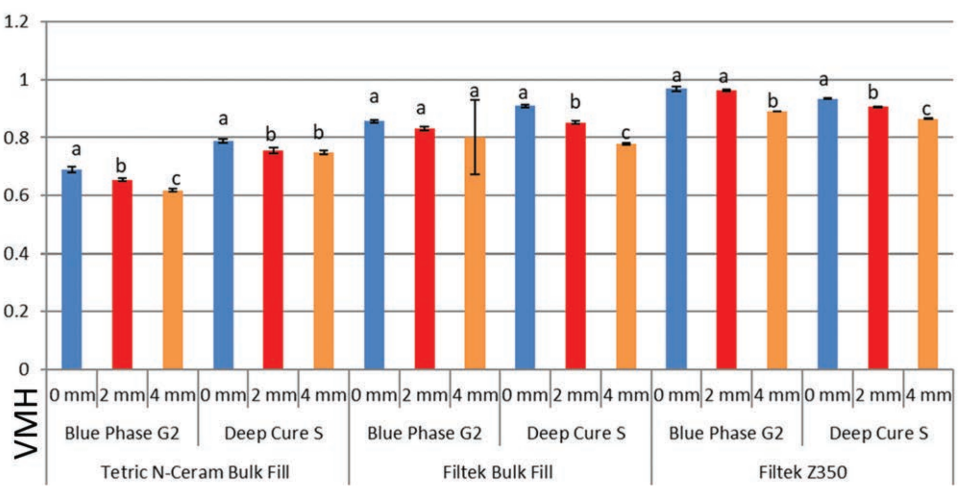

Figure 4. *Bar chart of mean (± SD) microhardness (VMH) ratios for full (4 mm) thickness. Lowercase superscript letters show differences within distances for each material and light curing unit.*

Table 4: *Results of Two-way ANOVA Showing Mean (± SD) VMN Ratios for the Full Thickness and Significant Differences Between the Three Distances for Each Material and LCU Combination*

Material	Curing Type	Light Tip Distance (mm)	Mean[a]	Standard Deviation	Df	Mean Square	F	Sig
Tetric N-Ceram Bulk Fill	Blue phase G2	0	0.689 a	0.011	2	0.013	235.75	0.000
		2	0.654 b	0.005				
		4	0.618 c	0.005				
	Deep Cure S	0	0.787 a	0.007	2	0.004	61.66	0.000
		2	0.756 b	0.010				
		4	0.748 b	0.007				
Filtek Bulk Fill	Blue phase G2	0	0.856 a	0.006	2	0.008	1.33	0.280
		2	0.831 a	0.008				
		4	0.801 a	0.130				
	Deep Cure S	0	0.909 a	0.005	2	0.043	3113.96	0.000
		2	0.852 b	0.004				
		4	0.778 c	0.002				
Filtek Z350	Blue phase G2	0	0.969 a	0.008	2	0.009	343.61	0.000
		2	0.962 a	0.003				
		4	0.891 b	0.000				
	Deep Cure S	0	0.934 a	0.002	2	0 .006	1380.30	0.000
		2	0.906 b	0.001				
		4	0.865 c	0.002				

[a] *Lowercase letters show the differences within distances for each material and light-curing unit.*

0 mm), whereas the lowest (29.96±0.51) was displayed with the Tetric N-Ceram Bulk Fill (DeepCure-S, 4 mm) (Figure 7).

The one-way ANOVA analysis showed significant differences between the LCU types (p<0.05) for all locations (Table 8). Multiple regression was run to predict the DC (all locations) for the material, curing type, and distance of the light cure tip. The DC was predicted with statistical significance by these variables, p < 0.0005. All three variables added significantly to the prediction, p < 0.05 for all locations except for the bottom where only two variables (the LCU type and the LC tip distance) added to the prediction. Moreover, there was a statistically significant difference identified between the materials, curing type, and tip distances (p<0.05). The DC showed a significant reduction with increasing distance of the LCU from the composite resin surface (Table 9).

Table 5: *Multiple Regressions for Full-Thickness VMN Values*

Coefficients							
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
Constant	0.615	0.018		33.89	0.000	0.580	0.651
Material	0.109	0.005	0.807	21.04	0.000	0.099	0.120
LCU	0.043	0.008	0.212	5.52	0.000	0.028	0.058
Distance	-0.037	0.005	-0.297	-7.75	0.000	-0.046	-0.028
F (3,146)=177.753			R2=0.785			p<0.0005	

Table 6: *Result of Two-way ANOVA Showing Mean (±SD) of DC Values and Significant Differences Between the Three Distances for Each Material and LCU for All Three Locations (Top, Middle, and Bottom) Combination*

Material LCU	Tip mm	Top Mean (SD)[a]	2 mm Mean (SD)[a]	Bottom Mean (SD)[a]	% DC Reduction LC Distance		Bottom / Top
					Top	Bottom	Full
Tetric N-Ceram Blue phase G2	0	68.95 a (.409)	67.64 a (.194)	64.51 a (.936)	95 (2/0)	89 (2/0)	94 (0)
	2	65.17 b (.493)	63.21 b (.387)	57.48 b (.133)	77 (4/2)	61(4/2)	88 (2)
	4	50.39 c (.144)	49.51 c (.143)	35.30 c (.408)	73 (4/0)	55 (4/0)	70 (4)
Tetric N-Ceram Deep Cure S	0	66.64 a (.150)	65.98 a (.557)	63.97 a (.733)	93 (2/0)	85 (2/0)	96 (0)
	2	61.74 b (.477)	60.49 b (.130)	54.58 b (.746)	80 (4/2)	55 (4/2)	88 (2)
	4	49.30 c (.520)	47.54 c (.168)	29.96 c (.511)	74 (4/0)	47 (4/0)	61 (4)
Filtek Bulk Fill Blue phase G2	0	70.17 a (.373)	68.90 a (.497)	65.56 a (.211)	95 (2/0)	92 (2/0)	93 (0)
	2	66.54 b (.148)	65.50 b (.099)	60.53 b (.111)	79 (4/2)	62 (4/2)	91 (2)
	4	52.47 c (.074)	50.41 c (.089)	37.66 c (.366)	75 (4/0)	57 (4/0)	72 (4)
Filtek Bulk Fill Deep Cure S	0	67.62 a (.118)	65.60 a (.147)	64.19 a (.531)	95 (2/0)	88 (2/0)	95 (0)
	2	64.33 b (.287)	62.44 b (.130)	56.37 b (.297)	78 (4/2)	61 (4/2)	88 (2)
	4	50.31 c (.120)	48.44 c (.089)	34.45 c (.164)	74 (4/0)	54 (4/0)	68 (4)
Filtek Z350 Blue phase G2	0	65.42 a (.131)		63.36[a] (.091)	96 (2/0)	92 (2/0)	97 (0)
	2	62.48 b (.097)		58.52[b] (.126)	84 (4/2)	61 (4/2)	94 (2)
	4	52.38 c (.096)		35.53[c] (.140)	80 (4/0)	56 (4/0)	68 (4)
Filtek Z350 Deep Cure S	0	62.41 a (.087)		59.61[a] (.092)	94 (2/0)	92 (2/0)	96 (0)
	2	58.57 b (.130)		54.57[b] (.117)	79 (4/2)	56 (4/2)	93 (2)
	4	45.99 c (.462)		30.32[c] (.448)	74 (4/0)	51 (4/0)	66 (4)

[a] *Lowercase letters show the differences within distances for each material as well as the light-curing unit ($p<0.001$) for all locations.*

DISCUSSION

In the present study, the effects of different LCUs and tip distances were tested on the polymerization efficiency of bulk-fill composites. The results of this study showed that all tested RBC materials presented higher DCs when cured with the Bluephase G2 LCU compared to the DeepCure-S LCU. Therefore, the first null hypothesis was rejected. Polywave LED LCUs are used to activate a wider range of photoinitiators, some of which require shorter wavelengths of light, and due to that narrow-spectrum LED LCUs emit very little light below 420 nm, single-peak LED lights are not very effective and might produce weaker RBC restorations.[17] This is in agreement with the results reported by Price and others,[18] who compared the effects of second- and third-generational LED LCUs on the microhardness of various RBCs.

When cured with the Bluephase G2 LCU, the Filtek Bulk Fill Posterior indicated a significantly higher DC at the top and the bottom layers than the Tetric N-Ceram Bulk Fill and the Filtek Z350 XT RBC materials. However, there were no significant differences observed at the 2 mm depth. These results are quite surprising considering that the Bluephase G2 is a polywave unit with an ultraviolet light spectrum (– 410 nm) which excites the Ivocerin (bis (4-methoxybenzoyl) diethylgermane Ge-3) initiator that is present in the Tetric N-Ceram. However, the monowave DeepCure-S LCU has a higher light irradiance than the Bluephase G2 with a wavelength covering the 440-500 nm range, that is the excitation peak of Ivocerin (408-440 nm). Also, previous studies reported limited penetration of the ultraviolet wavelengths into the composite as they get depleted in its top layer.[11] Therefore, it is likely that other factors related to the LCU or the materials also influence the results. The presence of multiple chips in the head of the Bluephase G2 LCU may lead to more even light distribution at the surface and throughout the composite.

Shimokawa and others reported that the total amount of light reaching the bottom of the 4-mm-thick specimens was only about 10% of the light delivered to the top, and

Table 7: *Scheffe Post-Hoc Comparison of the Mean Difference in DC Between the Different Materials, Light Cure Units, and Tip Distances for All Three Locations (Top, Middle, and Bottom)*

Dependent Variables	Location	Mean Difference			Std Error	Sig	Significance Between LC Tip Distances
		0-2	2-4	0-4			
Tetric N Ceram X Blue Phase G2	Top	3.78	14.77	18.56	0.169	<0.001	0 mm > 2 mm > 4 mm
	Middle	4.42	13.69	18.12	0.117	<0.001	
	Bottom	7.03	22.17	29.20	0.266	<0.001	
Tetric N Ceram X Deep Cure S	Top	4.89	12.44	17.34	0.169	<0.001	
	Middle	5.49	12.94	18.44	0.154	<0.001	
	Bottom	9.38	24.62	34.00	0.300	<0.001	
Filtek Bulk Fill X Blue Phase G2	Top	3.63	14.07	17.70	0.105	<0.001	0 mm > 2 mm > 4 mm
	Middle	3.39	15.08	18.48	0.132	<0.001	
	Bottom	5.02	22.87	27.90	0.112	<0.001	
Filtek Bulk Fill X Deep Cure S	Top	3.28	14.01	17.30	0.086	<0.001	
	Middle	3.15	14.00	17.15	0.055	<0.001	
	Bottom	7.81	21.92	29.74	0.162	<0.001	
Filtek Z350 X Blue Phase G2	Top	2.94	10.09	13.03	0.069	<0.001	0 mm > 2 mm > 4 mm
	Bottom	4.84	22.99	27.83	0.076	<0.001	
Filtek Z350 X Deep Cure S	Top	3.83	12.58	16.41	0.178	<0.001	
	Bottom	5.03	24.24	29.28	0.172	<0.001	

the spectral radiant power ratio of the delivered violet to blue light dropped from 26% (top) to only 2% at the bottom of the RBC specimen. This occurs as the light is used, absorbed, or reflected by the specimen during the polymerization reaction. However, the reduced amount of light as well as the limited penetration of the violet wavelengths may lead to inadequate polymerization in the deepest regions of the restorations, especially for the Tetric N-Ceram Bulk Fill.[19]

The DC of the top surface decreases significantly with an increased LCU tip distance. For all materials, a significant drop in the DC was quite evident at the 4 mm distance in comparison with the 0 and 2 mm distances. Therefore, the second null hypothesis was rejected. Moreover, the Tetric N-Ceram Bulk Fill had a lower DC than the Filtek Bulk Fill Posterior, which was in agreement with a previous study.[20] This difference in the DC results is probably due to a varying matrix and filler content of the two materials. Filtek Bulk Fill Posterior was reported to have uniformly small filler particles (1-3 μm), whereas the Tetric N-Ceram Bulk Fill was demonstrated to contain a wide range of particle sizes (1-30 μm) of prepolymerized resin particles and aggregates that were previously filled with fused silica, which could possibly affect its mechanical properties.[21] Regarding the microhardness at 4 mm, all ratios for the Tetric N-Ceram Bulk Fill cured by either LCU were below the acceptable level of 0.8 (or 80%). As

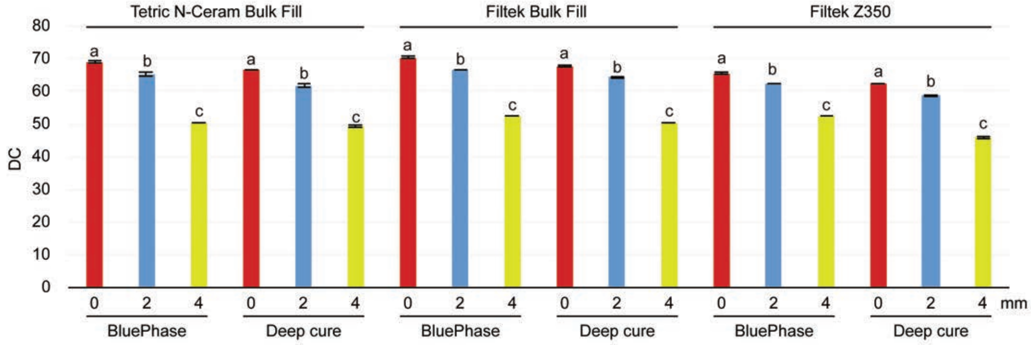

Figure 5. *Bar chart of mean (± SD) degree of conversion (DC) values (top 0 mm). Lowercase superscript letters show differences within distances for each material and light curing unit.*

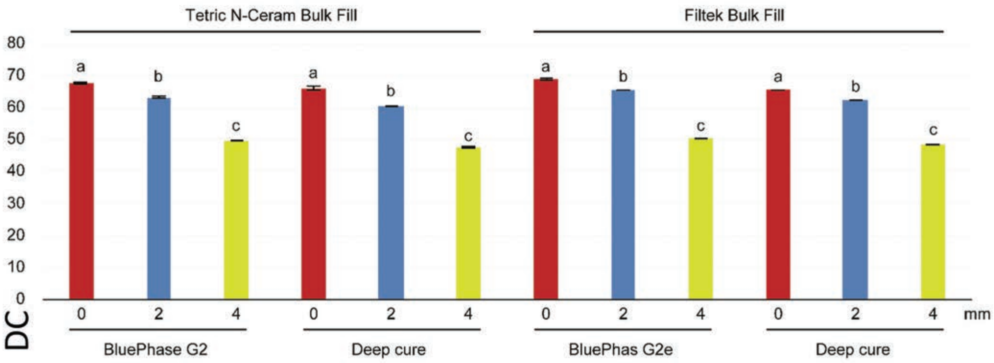

Figure 6. *Bar chart of mean (± SD) degree of conversion (DC) values (middle 2 mm). Lowercase superscript letters show differences within distances for each material and light curing unit.*

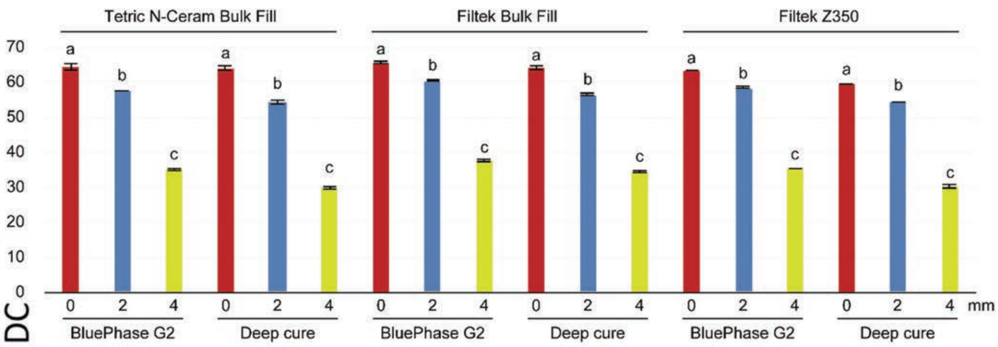

Figure 7. *Bar chart of mean (± SD) degree of conversion (DC) values (bottom 4 mm). Lowercase superscript letters show differences within distances for each material and light curing unit.*

for the Filtek Bulk Fill Posterior, all values were above 0.8 except for the 4 mm distance with the DeepCure-S. This is a direct result of the higher DC displayed by this material.

Similar to the DC results, the microhardness values for the Filtek Bulk Fill Posterior were higher than those of the Tetric N-Ceram Bulk Fill when cured with the Bluephase G2 LCU. Generally, all materials exhibited significantly lower microhardness values when cured with the DeepCure-S LCU, with the Tetric N-Ceram Bulk Fill revealing the lowest bottom-to-top surface VMN ratios. Therefore, the third null hypothesis was rejected. The spectrum emission for the Bluephase G2 and the Deep Cure S at 0, 2, and 4 mm distances for 20 seconds showed that the DeepCure-S LCU had a significant drop in the absolute irradiance from 82 to 62 mW/cm^2/nm while the Bluephase G2 presented a minor drop, which might explain the less-than-optimal performance of this LCU at greater distances.

According to Price and others,[18] several different types of LED chips are used by third-generation LED LCUs for the delivery of a broader spectral output in comparison with the narrower spectral output of second-generation LCUs, which can result in better mechanical properties of the RBCs. Another possible explanation is that the DeepCure-S has a collimated beam and higher irradiance and can, therefore, still reach photoinitiators at greater depths.[22]

Table 8: *One-way ANOVA Showing a Statistically Significant Difference Between Cure Types (p<0.05) for All Locations*

LCU	Location	Mean	Std Error	95% Confidence Interval		Sig *p*<0.05
				Lower Bound	Upper Bound	
Blue Phase G2	Top	61.556	0.037	61.483	61.629	0.00
Deep Cure S		58.551	0.037	58.478	58.625	0.00
Blue Phase G2	Middle	60.86	0.035	60.79	60.93	0.00
Deep Cure S		58.41	0.035	58.34	58.48	0.00
Blue Phase G2	Bottom	53.16	0.056	53.05	53.27	0.00
Deep Cure S		49.78	0.056	49.67	49.89	0.00

Table 9: *Multiple Regression Results for DC (Top Surface, 2 mm, and Bottom)*

Model		Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B	
		B	Std Error	Beta	t	Sig	Lower Bound	Upper Bound
Top	Material	-0.848	0.304	-0.083	-2.78	0.006	-1.45	-0.246
	LCU	-2.71	0.456	-0.177	-5.96	0	-3.619	-1.818
	Distance	-8.56	0.279	-0.912	-30.69	0	-9.115	-8.012
	F (3,146)=328.448			R2=0.871			*p*<0.0005	
2 mm	Constant	79.64	1.1		72.24	0	77.45	81.82
	Material	1.15	0.441	0.073	2.61	0.01	0.279	2.02
	LCU	-2.44	0.441	-0.156	-5.55	0	-3.32	-1.57
	Distance	-9.02	0.27	-0.938	-33.42	0	-9.56	-8.49
	F (3,116)=385.037			R2=0.909			*p*<0.0005	
Bottom	Constant	86.33	1.6		53.85	0	83.165	89.501
	Material	0.03	0.459	0.002	0.065	0.948	-0.877	0.937
	LCU	-3.19	0.687	-0.123	-4.65	0	-4.55	-1.83
	Distance	-14.94	0.421	-0.94	-35.52	0	-15.77	-14.11
	F (3,146)=427.798			R2=0.898			*p*<0.0005	

A quite alarming finding is the very low DC Filtek Z350 XT value seen at 4 mm LCU distance, especially at the bottom surface with the DeepCure-S despite the shorter distance of 6 mm that is to be traveled by the light, as opposed to 8 mm with bulk-fill materials. This indicates that the selection of the LCU is critical in deep cavities even with the incremental placement technique.

The results of this study confirmed that increasing the distance between the light tip and the resin composite can affect the light intensity which reaches the restorative material and can interfere with the efficacy of the polymerization, leading to weaker mechanical properties of the final restorative RBC material, especially at the deepest part of the restoration. These findings are in agreement with other studies that have stated that the effective polymerization of RBC materials is mainly dependent on the distance between the LCU tip and the restoration surface.[20,23] A similar result was reported in a recent study conducted by Ilie,[24] who concluded that bulk-fill materials did not tolerate variations in exposure distance as well as they tolerate small variations in the centricity of the LCU. Also, in this study, low VMH was shown by the Tetric N-Ceram Bulk Fill at depths larger than 3 mm, the author suggested that the lower filler content and the presence of prepolymerized particles might play a significant role.

The microhardness ratios at the top surface of all tested materials were significantly higher than the microhardness at the bottom surface in all light tip distances. This might be because more sufficient light energy reaches the photoinitiators at the top surface than at the bottom as the intensity of the light decreases while passing through the entire thickness of the bulk-fill material due to scattering and wavelength depletion. This effect was demonstrated in this study when significant differences in the DC and microhardness values were observed at a distance of 0 mm in comparison with those at 2 and 4 mm distances. However, the Filtek Bulk Fill Posterior MH values were not as significantly affected by the distances when cured with the Bluephase G2 LCU, although the variability of VMH ratios greatly increased at a distance of 4 mm. Catelan and others[25] reported that significantly lower irradiance may reach the surface of the resin in the tooth 2-8 mm away from the light tip. Moreover, the various areas of the resin might receive different amounts of light due to scattering and light attenuation, resulting in the perceived increased variability.[22] Another point to remember is that the results were reported as VMN ratios, therefore, even if the ratios remain high, the actual values might be affected by the distance and the efficiency of the curing is compromised.

The physical properties evaluated in this study are important predictors of clinical behavior of RBCs.

Microhardness enables the material to resist deformation, indentation, and scratching and predicts their resistance to abrasion and wear when used for occlusal restorations. Degree of conversion is significantly correlated to many important composite material characteristics, such as mechanical properties, volumetric shrinkage, wear resistance, and monomer elution. When the degree of conversion is low, the release of unreacted monomers from resin composite materials is high and it can induce undesirable biological responses. Therefore, utmost care must be exercised to ensure efficient curing of the resin-based restorative material particularly in deep cavity preparations.[26,27]

CONCLUSIONS

The Bluephase G2 LED LCU (polywave) revealed better polymerization efficiency than the DeepCure-S LED LCU (monowave). However, the DeepCure-S showed slightly better results in deeper areas. Increasing the distance between the LCU tip and the restoration surface was demonstrated to have a significantly detrimental influence on the mechanical properties of RBC materials. The DC and VMN values among the studied bulk-fill materials were significantly affected by the material composition and curing protocols.

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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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