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Evaluation of the Depth of Cure by Microhardness of Bulk-Fill Composites with Monowave and Polywave LED Light-Curing Units

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Featured Application: This study helps dental professionals select the most effective light-curing units for achieving optimal depth of cure in bulk-fill composites, enhancing the quality and longevity of dental restorations.

Abstract: This study aimed to evaluate the depth of cure (DoC) of bulk-fill composite resins, measured by the bottom-to-top Vickers microhardness ratio, using different light-curing units (LCUs): single-wave LED, polywave LED, and halogen. Six bulk-fill composites—Tetric EvoCeram Bulk Fill, X-tra base, SonicFill, Venus Bulk Fill, SDR, and Filtek Bulk Fill—were tested. Four LCUs, including one halogen (Elipar Trilight) and three LEDs (Demi Ultra, Valo, and Bluephase style), were employed for polymerization. Vickers hardness measurements were taken at depths of 1 mm to 5 mm. One- and two-way ANOVA ($\alpha = 0.05$) were used for data analysis. The results revealed significant differences in microhardness and microhardness ratios among the composites at depths of 4 mm and beyond, depending on the LCU used. It was observed that most bulk-fill composites showed an adequate DoC up to 4 mm, but the effectiveness varied with different LCUs. Importantly, polywave LED LCUs did not exhibit a superior advantage in achieving depth of cure compared to monowave LED LCUs for composites containing multiple photoinitiators. These findings suggest that while several factors affect the DoC, the type of LCU plays a crucial role, and polywave LEDs may not offer additional benefits over monowave LEDs.

Keywords: composite resin; bulk fill; microhardness; microhardness ratio; light-curing units (LCUs); monowave LED; polywave LED; halogen curing light; photopolymerization; Vickers hardness test; depth of cure; post-cure

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1. Introduction

Composite resins, when cured by light-curing units (LCUs), exhibit a degree of conversion ranging from 45% to 75%, depending on various factors related to the resin composition and light-curing parameters [1]. These factors include irradiance energy, wavelength range, resin shade, opacity, filler size, and loading [2]. Insufficient polymerization (IP) can adversely affect the mechanical properties of composite resins and result in the leaching of unpolymerized monomers, which may pose biocompatibility concerns [3]. The degree of polymerization (DP) of composite resins, as well as mechanical properties like microhardness, is diminished as a function of depth because a lower amount of light is reaching deeper in its mass due to scattering, absorption, and light reflection [4]. Thus, the uniform polymerization of the material throughout its depth is not achieved because of radiation, as it passes through the mass of the composite resin (CR) and undergoes scattering, reflection, and absorption, resulting in a loss of power. This leads to non-uniform polymerization across the entire volume of the composite resin (i.e., the restoration does not exhibit consistent physical, mechanical, and chemical properties throughout its volume) [5]. Moreover, the further the composite resin (CR) layer is from the light source, the greater the energy loss becomes. This issue is particularly significant in bulk-fill composites, as they are applied in a single layer rather than by using the layering technique (successive thin layers) [6]. Consequently, the depth of cure (DoC) gains even greater clinical importance in these cases [7]. DoC refers to the minimum acceptable level of polymerization required to adequately cure the material. Also, DoC can be assessed using direct methods such as FTIR and Raman spectroscopy [1] or indirect methods such as the scrape-back length technique [2] and microhardness testing [3,4]. A bottom-to-top microhardness ratio of 80% is commonly used as a threshold to indicate adequate DoC for composite resins. While this ratio is somewhat arbitrary, it is based on the study by Watts et al. [4] and has gained widespread acceptance in the field [5–9]. In regular CR, this threshold is typically achieved with increments up to 2 mm. However, in bulk-fill composites, which are cured in larger increments of up to 4–5 mm, achieving an adequate depth of cure becomes even more critical [10,11].

Historically, camphorquinone (CQ) and a tertiary amine have been the primary photoinitiator systems used in light-cured composite resins, with CQ exhibiting an absorption peak around 460 nm in the blue light spectrum [12]. However, CQ's yellow color limits its use in highly aesthetic applications, prompting the introduction of alternative photoinitiators such as phenylpropanedione (PPD) and Lucirin-TPO (TPO), which absorb light in the violet or ultraviolet B (UVB) range [13]. While halogens and plasma are LCUs that emit a broad spectrum of light between 375 nm and 510 nm and can effectively cure resins containing these photoinitiators, they have drawbacks such as decreased irradiance over time, heat generation, and short bulb lifespan [14,15]. To address these issues, light-emitting diode (LED) LCUs were developed, offering narrow-spectrum emission in the blue region (450–470 nm) with high radiant power, effectively polymerizing resins containing CQ as the sole photoinitiator [16]. However, the efficacy of single-peak LED LCUs is limited for resins with additional photoinitiators like PPD, TPO, and Ivocerin, as they require broader spectrum light for activation. Unfortunately, manufacturers often provide limited information on the photoinitiators used in their composite formulations, complicating the choice of optimal curing light [17]. The advent of polywave LED LCUs aimed to overcome these limitations by emitting both blue light and violet/UVB light to activate multiple photoinitiators. However, studies have shown that polywave LEDs may not consistently outperform monowave LEDs [12–14].

Bulk-fill composites represent a significant advancement in restorative dentistry, enabling the placement of increments up to 4 mm in thickness without compromising the degree of conversion (DC) [12–18], polymerization shrinkage, or marginal adaptation [11]. This improvement is possible due to the incorporation of larger fillers [12–22] and a reduction in color pigments [23], which enhances the depth of cure by increasing translucency. However, earlier versions of bulk-fill composites exhibited a grayish shade due to their higher translucency. Newer materials have addressed this issue by incorporating more efficient germanium-based photoinitiators [24] or utilizing different polymerization mechanisms, such as reversible addition–fragmentation chain transfer polymerization, which is less dependent on translucency [25–27]. Furthermore, there are studies demonstrating that bulk-fill composites can achieve a bottom-to-top hardness ratio exceeding 80% when cured at depths up to 4 mm using LED LCUs, indicating sufficient DoC [19–24,28–30], but others do not support these results [10,11,31–34]. Despite the proven advantages of polywave LED LCUs in curing conventional composites containing additional photoinitiators [12,17], their efficacy for bulk-fill composites remains insufficiently studied. Given that the performance of bulk-fill composites is heavily influenced by the effectiveness of different LCUs, it is crucial to explore their impact on depth-dependent microhardness for optimizing clinical outcomes and enhancing the longevity of restorations.

Thus, this study aimed to determine the depth of cure (DoC) of various bulk-fill composites by evaluating the bottom-to-top Vickers microhardness ratio using different LCUs, including monowave LED, polywave LED, and halogen LCUs. Additionally, this study compared the microhardness ratios of each bulk-fill composite at a depth of 4 mm across different LCUs to identify potential variations in curing efficacy. The null hypotheses tested were the following: (1) there are no significant differences in the Vickers Hardness Number (VHN) ratios for each bulk-fill composite tested with each LCU, and (2) all LCUs can effectively polymerize each bulk-fill composite up to a depth of 4 mm.

2. Materials and Methods

Six bulk-fill composite resins were evaluated in this study: Tetric EvoCeram Bulk Fill (Ivoclar Vivadent), X-tra Base (Voco), SonicFill (Kerr), Venus Bulk Fill (Heraeus), SDR (Caulk/Dentsply), and Filtek Bulk Fill flowable restorative (3M/ESPE) (Tables 1 and 2).

Table 1. Materials of the present study and their characteristics.

Material	Code	Type	Shade	Manufacturer Increment Thickness	Manufacturer Increment Irradiation Time, LCU Power	Filler % (wt, Vo)	Lot Number	Manufacturer
Venus Bulk Fill	Ve	Flowable nanohybrid	Universal	4 mm	20 s, >550 mW/cm^2	65/ 38	010105	Heraeus Kulzer GmbH Wasserburg, Germany
X-tra Base	XT	Flowable	A2	4 mm	10 s, 500–800 mW/cm^2	75	1420374	Voco, Cuxhaven, Germany
SDR	SDR	Flowable	Universal	4 mm	20 s, >550 mW/cm^2	68	1406000588	Dentsply, Charlotte, NC, USA
Tetric EvoCeram Bulk Fill	Te	Medium viscosity	Universal A (IVA)	4 mm	10 s, >500 mW/cm^2	76–77/ 53–54	T29056	Ivoclar Vivadent, AG, Schaan, Liechtenstein
SonicFill	So	Medium viscosity	A3	5 mm	20 s > 550 mW/cm^2 20 s Demi plus	83.5	5236129	Kerr, Brea, CA, USA
Filtek Bulk Fill flowable restorative	Fi	Flowable	A3	4 mm	20 s > 550–1000 mW/cm^2 10 s >1000 mW/cm^2	64.5/ 42.5	N561441	3M/ESPE St. Paul, MN, USA

Table 2. Synthesis of materials used in the present study.

Material	Code	Type	Matrix	Filler	Filler % (wt, Vo)	Lot Number	Manufacturer
Venus Bulk Fill	Ve	Flowable nanohybrid	UDMA, EBADMA	Ba-Al-F silicate glass YbF, SiO_2, 0.02–5 μ	65/ 38	010105	Heraeus Kulzer GmbH Wasserburg, Germany
X-tra Base	XT	Flowable	Aliphatic dimethacrylate, Bis-EMA, UDMA, EBADMA	SiO_2 glass, oxide	75	1420374	Voco, Cuxhaven, Germany
SDR		Flowable	UDMA, EBADMA, TEGDMA	Ba-Al-F silicate glass Sr-Al-F silicate glass	68	1406000588	Dentsply, Charlotte, NC, USA
Tetric EvoCeram Bulk Fill	Te	Medium viscosity	Bis-GMA, UDMA	Ba-Al-Si glass YbF	76–77/ 53–54	T29056	Ivoclar Vivadent, AG, Schaan, Liechtenstein
SonicFill	So	Medium viscosity	BisGMA, TEGDMA, Bis-EMA, SIMA	Silicate glass	83.5	5236129	Kerr, Brea, CA, USA
Filtek Bulk Fill flowable restorative	Fi	Flowable	Bis-GMA, UDMA, Bis-EMA	YbF 0.1–5 μ Zr silicate glass 0.01–3.5 μ	64.5/ 42.5	N561441	3M/ESPE St. Paul, MN, USA

Four light-curing units (LCUs) were used for polymerization: one halogen LCU, Elipar Trilight (3M/ESPE); one monowave LED, Demi Ultra (Kerr); and two polywave LEDs, Valo (Ultradent) in standard power mode and Bluephase Style (Ivoclar) (Table 3).

Table 3. Light-curing units used in the present study.

LCU	Code	Power Manufacturer	Wavelegth	Serial Number	Manufacturer
Elipar Trilight	HA	800 mW/cm^2	460 nm		3M/ESPE, St. Paul, MN, USA
Demi Ultra	De	1100 mW/cm^2	450–570 nm	786010009	Kerr, Brea, CA, USA
Bluephase Style	BS	1100 mW/cm^2	385–515 nm	1100017240	Ivoclar Vivadent, Vivadent, AG, Schaan, Liechtenstein
Valo	VA	1000 mW/cm^2	395–480 nm	VO 4582 Lot 86020	Ultradent Products Inc., South Jordan, UT, USA

2.1. Specimen Preparation

Cylindrical composite specimens measuring 8 mm in height and 10 mm in diameter were fabricated using a black Teflon mold with a slightly tapered cylindrical cavity (Figure 1).

Figure 1. The Teflon mold used for the fabrication of the specimens.

Sonic fill specimens were dispensed into the mold using their proprietary ultrasonic delivery system to adjust viscosity. Ten specimens were prepared for each of the six composites. The mold was placed over a celluloid strip, covered with a glass slide, and filled with composite resin, and then another celluloid strip and glass slide were placed on top. This assembly was compressed using a hydraulic press to eliminate excess material and minimize internal porosity. The glass slide was removed, and the composite resin was polymerized for 20 s using the respective LCU. After polymerization, specimens were scraped to remove uncured material, and therefore they did not possess the same length. They were then embedded in a cylindrical mold filled with epoxy resin and allowed to set for 24 h. Specimens were then sectioned longitudinally using a low-speed diamond saw under water cooling (Buehler Isomet, Diamond Cut-off Wheel MOD10, Struers, Copenhagen, Denmark) to produce rectangular slabs containing the specimens cut longitudinally, maintaining perpendicularity to the top surface and staying parallel to the specimen's long axis (Figures 2 and 3). The slabs were polished using 600-grit metallographic abrasive paper under water cooling (Dap V, Struers) to create a flat surface with minimal roughness, suitable for accurate indentation measurements. Specimens were stored at 37 °C for 24 h before testing.

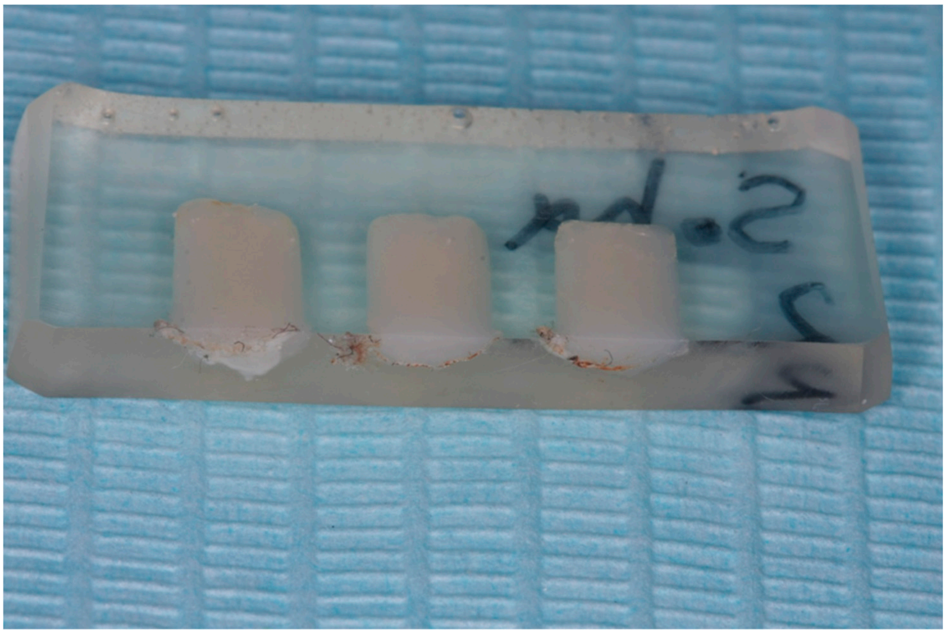

Figure 2. Three SonicFill specimens polymerized with Blue Style, embedded in epoxy resin, sectioned, and polished.

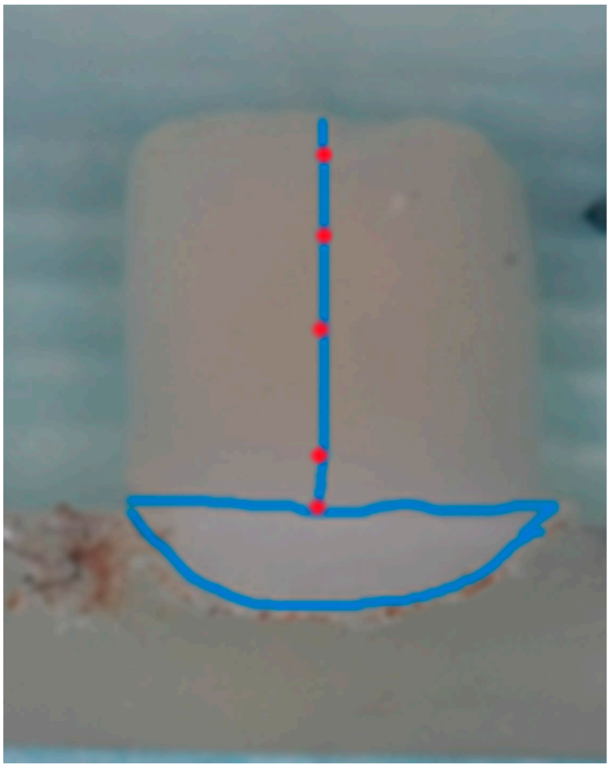

Figure 3. The cylindrical rod of the cured specimen is embedded in epoxy resin and sectioned longitudinally to produce a slab containing half of it. The illustrated red points represent the surface, 0.5 mm, 2 mm, 3 mm, and 4 mm depth points where the microhardness measurements were performed.

2.2. Vickers Hardness Measurement

Vickers hardness measurements were performed using a Vickers indenter (Vickers pyramid: diamond right pyramid with a square base and an angle of 136° between opposite faces at the vertex) with a 200 gf (1.96 N) load and a 15 s dwell time (HMV 2000, Shimadzu Corp., Tokyo, Japan). Indentations were made longitudinally on each specimen at depths of 0.5 mm, 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, and, where possible, 6 mm and 7 mm from the irradiated surface (Figures 2 and 3). Three indentations were created at each depth and averaged. Measurements of indentation diagonals were taken under an optical microscope (Leica DM4000 B, Leica Microsystems CMS GmbH, Mannheim, Germany), and Vickers hardness (VH) was calculated using the formula VH = 1.8544 × Fd2VH = 1.8544\times\frac{F}{d^2}VH = 1.8544 × d2F, where FFF is the applied load (kgf) and ddd is the average diagonal length of the indentation (mm) (Figure 4).

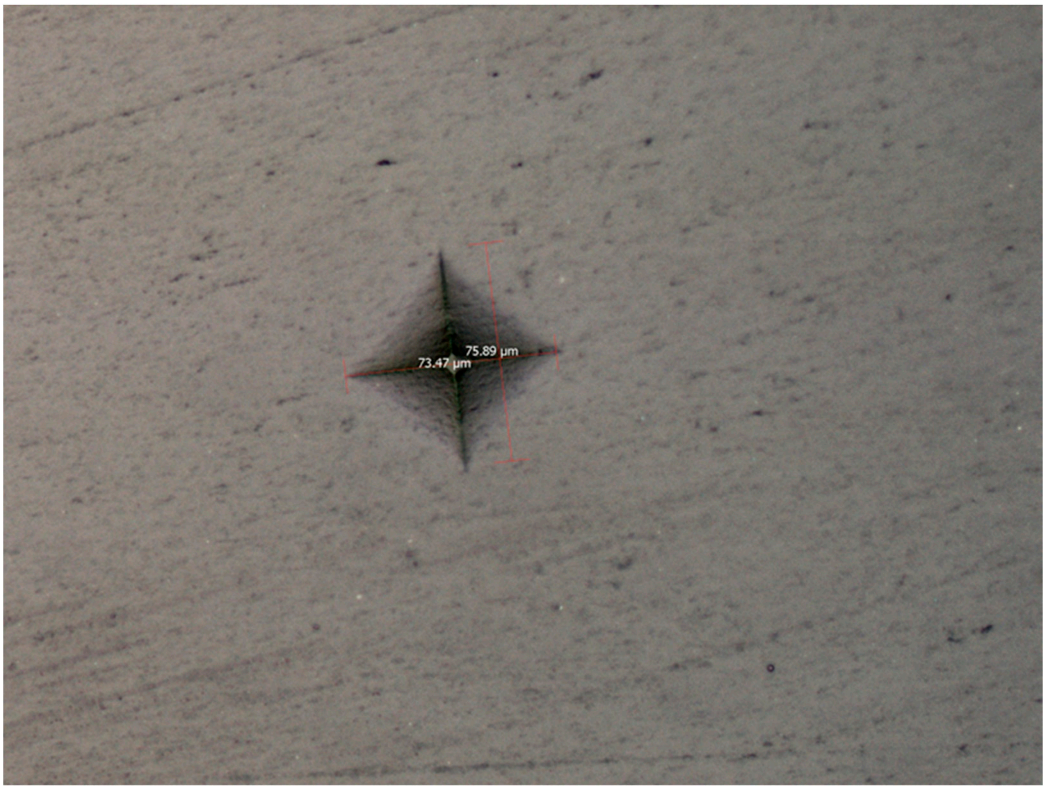

Figure 4. The Vickers microhardness indentation and the dimensions of the diagonals of a Tetric Evo Ceram Bulk Fill specimen polymerized by the Elipar LCU at a depth of 2 mm.

2.3. Statistical Analysis

The statistical analysis in this study was designed to evaluate the effects of different factors—composite material, light-curing unit (LCU), and depth—on the Vickers hardness (VH) of bulk-fill composite resins. Our analysis aimed to provide a comprehensive understanding of the influence of these variables on the depth of cure (DoC) by employing a combination of one-way and two-way analysis of variance (ANOVA) tests, followed by post hoc testing to identify specific differences among groups. More specifically, one-way ANOVA was performed to analyze the Vickers hardness (VH) measurements at different depths (0.5 mm, 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, and, where possible, 6 mm and 7 mm) for each composite material and LCU combination separately. This test was used to determine whether there were statistically significant differences in the VH across various depths for each material and LCU. As suggested elsewhere, one-way ANOVA is appropriate in this context as it allows for the comparison of means across multiple groups (depths) to assess if at least one group (depth) differs significantly from the others [35]. The assumptions of one-way ANOVA, including the independence of observations, normality of VH distribution within each group, and homogeneity of variances, were checked. Normality was assessed visually using histograms and statistically using the Shapiro–Wilk test [36], while the homogeneity of variances was examined with Levene's test [37]. When significant differences were found ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post hoc test was used to identify which specific depths differed significantly from each other while controlling for type I errors across multiple comparisons [35]. Next, two-way ANOVA was conducted to evaluate the effects of two independent variables—composite material and LCU—on the VH at a clinically relevant depth of 4 mm. This analysis provided insight into both the individual effects of each factor (material and LCU) and any potential interaction effect between them on VH at 4 mm. An interaction effect would suggest that the influence of one factor (e.g., LCU) on the VH was dependent on the level of the other factor (e.g., composite material) [38]. The assumptions for two-way ANOVA, which were similar to those for one-way ANOVA, were checked, including independence, normality of VH within each group, and homogeneity of variances. Significant differences were further analyzed using Tukey's HSD post hoc test to determine which specific combinations of composite materials and LCUs differed significantly in terms of VH [35]. Finally, a two-way ANOVA was also conducted to examine the hardness ratio (bottom-to-top hardness ratio) across different depths, considering the LCU and composite material as independent variables. This analysis aimed to understand whether the curing depth efficacy, as indicated by the hardness ratios, was influenced by the type of composite and LCU used. The assumptions of the two-way ANOVA were met, as described above [35]. If significant differences were detected ($p < 0.05$), Tukey's HSD test was applied to identify the specific groups (combinations of LCU and composite material) that had significant differences in hardness ratios [38].

All statistical analyses were performed using IBM SPSS Statistics 22 (IBM, Armonk, NY, USA). The significance level was set at $\alpha = 0.05$ for all analyses. This comprehensive statistical approach allowed us to determine how Vickers hardness values change at increasing depths, evaluate the best-performing LCU and composite combinations at a significant depth of 4 mm, and understand the efficiency of different LCUs in curing composites at various depths. These findings provide valuable insights for optimizing the use of LCUs with different bulk-fill composite materials to achieve the best possible clinical outcomes.

3. Results

The microhardnesses at the selected depths for SDR, Filtek Bulk Fill, SonicFill, Tetri EvoCeram Bulk Fill, Xtra Base, and Venus Bulk Fill, polymerized by the four LCUs, are presented in Table 4. The ratio of hardness to the "surface" (0.5 mm) at the selected depths, for the bulk-fill composites polymerized by the four LCUs, are presented in Table 5.

Our analysis revealed the following key findings regarding the microhardness of bulk-fill composites at a 4 mm depth across different light-curing units (LCUs):

SDR: No statistically significant differences in microhardness were observed at the 4 mm depth compared to baseline for any of the LCUs tested. Additionally, there were no significant differences in microhardness among the various LCUs.

Filtek Bulk Fill flowable restorative: Similarly, no statistically significant differences in microhardness were found at the 4 mm depth compared to baseline for any of the LCUs. However, a statistically significant difference was observed between the halogen (Ha) LCU, which demonstrated a lower microhardness, and the other LCUs.

SonicFill: For most LCUs, there were no statistically significant differences in microhardness at the 4 mm depth compared to baseline, except for Va, which showed significantly lower microhardness. Additionally, significant differences were found between some of the LCUs, with the halogen (Ha) LCU showing a lower microhardness and the BS LCU exhibiting significantly higher microhardness values.

Table 4. Microhardness of bulk-fill composites at several depths from the irradiated surface by different light-curing units (BS stands for Bluephase Style, Ha for Elipar Trilight, Va for Valo, and De for Demi Ultra).

		SDR		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	43.8 ± 4.2^{1}	45.2 ± 2.5^{1}	55.9 ± 10.6^{1}	51.1 ± 2.8^{1}
2	45.3 ± 5.4^{1}	46 ± 4.4^{1}	58.2 ± 10.2^{1}	50.5 ± 5.8^{1}
3	45.3 ± 5.4^{1}	43.7 ± 6.6^{1}	57.3 ± 7.9^{1}	49.8 ± 6.4^{1}
4	$43.5 \pm 2.9^{1,a}$	$43.1 \pm 6.2^{1,a}$	$53.6 \pm 9.6^{1,2,b}$	$49.7 \pm 5.3^{1,a,b}$
5	40.8 ± 2.4^{1}	40.9 ± 7.1^{1}	$53.4 \pm 10.9^{1,2}$	46.7 ± 8.6^{1}
6	28 ± 9.3^{2}	36.6 ± 3.9^{1}	$50.9 \pm 14.4^{1,2}$	44 ± 11.1^{1}
7	8.1 ± 2.6^{3}		28.8^{2}	37.3 ± 12.8^{1}
8				
		Filtek Bulk Fill flowable restorative		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	$49.4 \pm 2^{1,2}$	41.7 ± 6.2^{1}	40.1 ± 5.4^{1}	$50.2 \pm 3.6^{1,2}$
2	50.2 ± 3.9^{1}	41.5 ± 5.9^{1}	40.1 ± 5.4^{1}	52 ± 1.7^{1}
3	$49.5 \pm 3.9^{1,2}$	40.1 ± 6.8^{1}	42.3 ± 1.8^{1}	51.4 ± 1.4^{1}
4	$45.2 \pm 4.9^{1,2,a,b}$	$36.3 \pm 6.8^{1,2,b}$	$40.2 \pm 4.1^{1,a,b}$	$48.7 \pm 2.1^{1,2,a}$
5	42.1 ± 4.6^{2}	$30 \pm 5.7^{1,2}$	$39.3 \pm 3^{1,2}$	$44.6 \pm 2.8^{2,3}$
6	30.5 ± 4.5^{3}	24.8 ± 2.9^{2}	$38.8 \pm 3.3^{1,2}$	$40 \pm 2.8^{3,4}$
7			$36 \pm 4.5^{1,2}$	36.1 ± 5.6^{4}
8			32 ± 3.3^{2}	
		SonicFill		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	114.3 ± 8.5^{1}	86.2 ± 10.5^{1}	111.3 ± 11.2^{1}	107.6 ± 9.5^{1}
2	113.3 ± 7.5^{1}	86.9 ± 11.6^{1}	104.8 ± 4.4^{1}	107.9 ± 11.4^{1}
3	110.2 ± 6.5^{1}	79.6 ± 14.9^{1}	$99 \pm 6.4^{1,2}$	$105.9 \pm 8.3^{1,2}$
4	$106.3 \pm 5.8^{1,a}$	$79.3 \pm 17.3^{1,c}$	$85.9 \pm 4.8^{2,3,b}$	$94.0 \pm 6.3^{1,2,3,a,b}$
5	99.8 ± 3.5^{1}	61.6 ± 23.1^{1}	74.7 ± 3.9^{3}	$90.6 \pm 9.8^{2,3}$
6	80.1 ± 16.7^{2}		49.4 ± 3.8^{4}	87.8 ± 4.7^{3}
7				
8				
		Tetric EvoCeram Bulk Fill		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	68.8 ± 6.6^{1}	67.6 ± 7.8^{1}	73.6 ± 8.6^{1}	72.7 ± 8.2^{1}
2	$64.5 \pm 3.5^{1,2}$	$64.2 \pm 6.6^{1,2}$	$67.5 \pm 4^{1,2}$	74.2 ± 7.5^{1}
3	$60.3 \pm 5.2^{1,2}$	$63.1 \pm 5.8^{1,2}$	$60.8 \pm 4.1^{2,3}$	75.6 ± 8^{1}
4	$52.6 \pm 4.7^{2,3,b}$	$61.1 \pm 6.6^{1,2,b}$	$57.1 \pm 6^{2,3,b}$	$75.3 \pm 5.8^{1,a}$
5	$42.6 \pm 13.1^{3,4}$	$57.7 \pm 5.7^{1,2}$	51.7 ± 6.2^{3}	72.5 ± 9.7^{1}
6	34.3 ± 2.2^{4}	55.1 ± 5.3^{2}	38.7 ± 6.2^{4}	71.5 ± 9.3^{1}
7				
8				
		XTra-Base		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	62.1 ± 0.5^{1}	78.4 ± 28.9^{1}	74 ± 4.7^{1}	83.3 ± 1.5^{1}
2	59.5 ± 2.8^{1}	80.8 ± 26.3^{1}	71.4 ± 7.4^{1}	81.8 ± 5^{1}
3	54 ± 7.4^{1}	75.7 ± 19.3^{1}	$67.4 \pm 5^{1,2}$	80.1 ± 6^{1}
4	$45.3 \pm 10.2^{1,b}$	$69.4 \pm 20.2^{1,a}$	$59.4 \pm 4.8^{2,3,a,b}$	$76.8 \pm 4.5^{1,2,a}$
5	33.8 ± 10.9^{1}	65.9 ± 16.1^{1}	50.6 ± 5.7^{3}	$66.8 \pm 5.1^{2,3}$
6	21.6 ± 4.2^{1}		40 ± 4.3^{4}	$60.7 \pm 6^{3,4}$
7			29.3 ± 2.8^{5}	51.1 ± 8.8^{4}
8				

Table 4. *Cont.*

Venus Bulk Fill				
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
0.5	35.1 ± 6.1 [1,2]	35.4 ± 6.7 [1]	32.4 ± 1 [1]	40.1 ± 5.4 [1]
2	35.5 ± 1.1 [1]	35.0 ± 6 [1]	32.5 ± 1.3 [1]	42.3 ± 1.8 [1]
3	35.4 ± 0.8 [1]	34.7 ± 5.9 [1]	32.9 ± 1.3 [1]	40.2 ± 4.1 [1]
4	34.0 ± 1.2 [1,2,A,b]	34.5 ± 6.1 [1,A,b]	31.8 ± 1.4 [1,b]	39.3 ± 3 [1,2,a]
5	31.8 ± 1.9 [1,2]	33.4 ± 5.8 [1]	31.2 ± 0.6 [1]	38.8 ± 3.3 [1,2]
6	27.7 ± 5.1 [2]	30.6 ± 5.8 [1]	31 ± 1.1 [1]	36 ± 4.5 [1,2]
7	19.9 ± 5.4 [3]	25.4 ± 6.5 [1]	26.5 ± 1.6 [2]	31.9 ± 3.3 [2]
8			26.5 ± 1.6 [2]	

The same numbers represent that there are no statistically significant differences in the microhardness of each material separately at different depths (within each column) ($p > 0.05$). The same letters represent that there are no statistically significant differences in the microhardness of each material, separately, at the depth of 4 mm (row) when polymerized by different LCUs ($p > 0.05$). In the fields where no measurement is recorded, this is because the material did not have an appropriate length, as it was too soft and was removed through abrasion.

Table 5. The ratio of hardness to the "surface" (0.5 mm) at the selected depths for the bulk-fill composites polymerized by the four LCUs (BS stands for Bluephase Style, Ha for Elipar Trilight, Va for Valo, and De for Demi Ultra).

SDR				
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	103.5 ± 10.3 [1,α]	101.6 ± 5.8 [1,α]	104.3 ± 3.6 [1,α]	98.7 ± 7.6 [1,α]
3	109.9 ± 20.8 [1,α]	96.6 ± 12 [1,2,α]	103.3 ± 8.1 [1,α]	97.1 ± 8.3 [1,α]
4	99.7 ± 9.8 [1,a,b]	95.2 ± 10.7 [1,2,b]	95.9 ± 1 [1,2,b]	97.1 ± 7.5 [1,a,b]
5	93.5 ± 6.6 [1,b]	90.2 ± 12.4 [1,2,b]	95.4 ± 2.5 [1,2,α,b]	90.8 ± 13 [1,b]
6	62.9 ± 17.6 [2,c]	80.9 ± 7.3 [2,b]	90.1 ± 8.2 [2,b]	85.6 ± 20 [1,b]
7	19.5 ± 7.8 [3,d]	-	57.1 ± 7.2 [3,b]	73.6 ± 21.8 [1,a,b]
8	-	-	-	-
Filtek Bulk Fill flowable restorative				
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	101.7 ± 6.3 [1,α]	99.7 ± 5.5 [1,α]	107.1 ± 16.4 [1,α]	104.1 ± 9.3 [1,α]
3	100.3 ± 4.5 [1,α]	96.0 ± 5.5 [1,2,α]	102.3 ± 20.2 [1,α]	102.7 ± 6.9 [1,α]
4	91.5 ± 8.1 [1,2,b]	86.7 ± 6.1 [2,b,c]	99.6 ± 16.3 [1,α,b]	97.3 ± 7.7 [1,2,α,b]
5	85.2 ± 7.2 [2,b,c]	71.9 ± 6.6 [3,c]	98.2 ± 15.3 [1,a,b]	89.0 ± 5 [1,2,3,b]
6	62.2 ± 11 [3,c]	61.2 ± 3.9 [3,c]	91.1 ± 17 [1,b]	80.3 ± 10.1 [2,3,b,c]
7	-	-	81.3 ± 17.9 [1,α]	73.4 ± 15. 6 [3,α,b]
8	-	-	-	-
SonicFill				
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	103.5 ± 10.3 [1,α]	101.1 ± 9.1 [1,α]	94.7 ± 7.9 [1,α]	100.3 ± 6.2 [1,α]
3	99.2 ± 4.7 [1,α]	92.1 ± 7.8 [1,2,α]	89.7 ± 11.3 [1,α]	99 ± 11.4 [1,α]
4	96.5 ± 4 [1,α,b]	92.5 ± 19.8 [1,2,b]	77.5 ± 5 [1,2,c,d]	87.6 ± 3.2 [1,2,b,c]
5	93.3 ± 6.4 [1,b]	70.8 ± 20.3 [2,c]	67.5 ± 5.9 [2,c]	84.3 ± 6.4 [2,b,c]
6	87.7 ± 6.8 [1,b]	-	46.6 ± 9.7 [3,d]	82 ± 7.7 [2,b]
7	69.9 ± 12 [2,a,b]	-	-	-
8	-	-	-	-

Table 5. *Cont.*

		Tetric EvoCeram Bulk Fill		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	$94.6 \pm 12.3^{1,\alpha}$	$95.2 \pm 3.1^{1,\alpha}$	$92.2 \pm 6.1^{1,\alpha}$	$102.3 \pm 3.1^{1,\alpha}$
3	$88 \pm 8.3^{1,2,\alpha}$	$93.7 \pm 6.5^{1,\alpha}$	$83.4 \pm 9.9^{1,2,\alpha}$	$104.1 \pm 2.7^{1,\alpha}$
4	$76.8 \pm 7.5^{1,2,3,c,d}$	$90.5 \pm 4.4^{1,2,b,c}$	$77.8 \pm 6.7^{1,2,c,d}$	$104.2 \pm 8.1^{1,a}$
5	$62.4 \pm 20.6^{2,3,c}$	$85.6 \pm 4.8^{1,2,b,c}$	$71.1 \pm 13.1^{1,2,3,c}$	$100.3 \pm 13.8^{1,a}$
6	$53 \pm 1.6^{3,c,d}$	$81.9 \pm 7.6^{2,b}$	$53.1 \pm 10.2^{3,c,d}$	$98.9 \pm 12.4^{1,a}$
7	-	-	-	-
8	-	-	-	-
		XTra-Base		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	$96 \pm 5.1^{1,\alpha}$	$104.6 \pm 10.6^{1,\alpha}$	$96.6 \pm 8.8^{1,\alpha}$	$98.3 \pm 5.7^{1,\alpha}$
3	$87 \pm 12.7^{1,2,\alpha}$	$100.4 \pm 17.3^{1,\alpha}$	$91.6 \pm 11.3^{1,\alpha}$	$96.3 \pm 7.9^{1,\alpha}$
4	$73 \pm 17^{1,2,d}$	$90.7 \pm 10^{1,b}$	$80.6 \pm 8.6^{1,2,b,c}$	$92.3 \pm 6^{1,2,b}$
5	$54.5 \pm 18^{2,3,d}$	$87.1 \pm 11.3^{1,2,b,c}$	$68.8 \pm 11^{2,3,c}$	$80.2 \pm 5.3^{2,3,b,c}$
6	$34.8 \pm 7.2^{3,d}$	$66.8 \pm 11.2^{2,b,c}$	$54.2 \pm 6.6^{3,4,c}$	$72.8 \pm 6.5^{3,4,b,c}$
7	-	-	$39.6 \pm 3.7^{4,c}$	$61.3 \pm 10^{4,b}$
8				
		Venus Bulk Fill		
Depth (mm)	**Bs**	**Ha**	**Va**	**De**
2	$103.7 \pm 20.2^{1,\alpha}$	$99.4 \pm 3.8^{1,\alpha}$	$100.2 \pm 3.6^{1,\alpha}$	$107.1 \pm 16.4^{1,\alpha}$
3	$104.1 \pm 24.2^{1,\alpha}$	$98.6 \pm 4.8^{1,\alpha}$	$101.5 \pm 3.5^{1,\alpha}$	$102.3 \pm 20.2^{1,\alpha}$
4	$99.7 \pm 20.6^{1,\alpha,b}$	$97.7 \pm 5.4^{1,\alpha,b}$	$98.3 \pm 3.2^{1,\alpha,b}$	$99.6 \pm 16.3^{1,\alpha,b}$
5	$93.72 \pm 23.2^{1,2,b}$	$94.7 \pm 6^{1,2,b}$	$96.3 \pm 3.2^{1,\alpha,b}$	$98.2 \pm 15.3^{1\ \alpha,b}$
6	$79.1 \pm 7.8^{1,2,b,c}$	$86.7 \pm 5.3^{2,b}$	$95.6 \pm 3.3^{1,\alpha,b}$	$91.1 \pm 17^{1,b}$
7	$58.\ 2 \pm 18.4^{2,b}$	$71.1 \pm 6.6^{3,\alpha,}$	$81.8 \pm 3.7^{2,\alpha}$	$81.3 \pm 17.9^{1,\alpha}$
8	-	-	68.6 ± 2.8^{3}	-

The same numbers represent that there are no statistically significant differences in the microhardness ratio between different depths for each material (within each column) ($p > 0.05$). The same letters represent that there are no statistically significant differences in the microhardness ratio of each material at several depths (no significant differences in each line) ($p > 0.05$). In the fields where no measurement is recorded, this is because the material did not have the appropriate length, as it was too soft and was removed through abrasion.

Tetric EvoCeram Bulk Fill: No significant differences in microhardness were found at the 4 mm depth compared to baseline for any of the LCUs, except for Va, which again exhibited significantly lower values. Additionally, the De LCU demonstrated a significantly higher microhardness compared to the other LCUs.

Xtra Base: Like the other materials, no statistically significant differences in microhardness were found at the 4 mm depth compared to baseline for most of the LCUs, except for Va, which showed a significantly lower microhardness. Notably, the De and Ha LCUs demonstrated significantly higher microhardness values.

Venus Bulk Fill: No statistically significant differences in microhardness were found at the 4 mm depth compared to baseline for most of the LCUs. However, a statistically significant difference was found with Va showing significantly lower microhardness values.

Overall, the microhardness of specimens cured with the Ha light-curing unit showed significantly lower values for all materials except SDR and XT compared to the other units at the 4 mm depth for each material, separately.

Furthermore, no statistically significant differences were observed in the microhardness ratio at the 4 mm depth among each material and curing unit separately, except for the Filtek light cured by the halogen LCU, which presented significantly lower values ($p < 0.05$).

Statistically significant differences in the microhardness ratio among the different materials polymerized by different curing lights were found at the 4 mm depth for SonicFill when cured with the Valo LCU, Tetric when cured with the Bluephase Style and Valo LCU, and Xtra-base when cured with the Bluephase Style LCU, which showed significantly lower values ($p < 0.05$), as well as for Tetric when cured with Demi Ultra, which demonstrated a higher value ($p < 0.05$) (Table 5).

4. Discussion

Significant differences were found in the VHN microhardness for each bulk-fill composite polymerized at a 4 mm depth and beyond. Significant differences were found in the microhardness of each material polymerized by the different curing units at the 4 mm depth. Therefore, the null hypothesis that there would be no significant differences in VHN microhardness for each bulk-fill composite tested for each LCU separately, as well as for each material light-cured by different curing units at the 4 mm depth, was rejected. Significant differences were found in the VHN microhardness ratio for several bulk-fill composites polymerized with different LCUs at the 4 mm depth. Therefore, the null hypothesis that all LCUs could effectively polymerize bulk-fill composites at a depth of 4 mm was rejected.

The findings of this study provide important insights into the curing effectiveness of different light-curing units (LCUs) on bulk-fill composites, particularly regarding depth of cure (DoC) and microhardness. We discuss our data more specifically in the following sections.

4.1. Microhardness and Light-Curing Unit (LCU) Effectiveness

Research by Santini et al. [12] and Lee et al. [13] demonstrated that polywave LEDs improved the DC and Knoop Hardness Number (KHN) of materials containing TPO, while monowave LEDs showed a higher DC in CQ-based composites. However, Sim et al. [14] reported that dual-peak LEDs performed similarly to single-peak LEDs and halogen LCUs for co-initiator composites, with some limitations in achieving sufficient DoC in deeper layers.

In our study, the radiant exitance measured was 12 J/cm^2 for Elipar Trilight (QTH), 21 J/cm^2 for Demi Ultra (single-wave), 20.6 J/cm^2 for BluePhase Style (multi-wave), and 20 J/cm^2 for Valo (multi-wave). Irradiation times were in line with manufacturer's recommendations for all materials. Specimens cured with the halogen (Ha) LCU showed significantly lower microhardness values at the 4 mm depth compared to the other LCUs, except for SDR and X-tra Base (XT). This is consistent with the lower energy output of the Ha LCU, resulting in reduced energy absorption by the composite. According to the reciprocity law, the degree of cure (DoC) depends on the total energy (irradiance × exposure time), with lower irradiance or exposure time leading to insufficient curing [6,7,39,40]. For the SDR material cured with the QTH LCU, no significant differences were observed compared to the rest of the curing units, and for XT, higher values than the polywave curing units were observed. This finding could be explained due to the high translucency of these materials. Bulk-fill composites with a higher percentage of the monomer TEGDMA, such as SDR, increase the flexibility and reactivity of the organic matrix and are prone to a higher degree of conversion [17,18,41,42]. In the present study, this was verified for the flowable bulk-fill composites tested, i.e., SDR, Filtek Bulk Fill, Xtra-Base, and Venus Bulk Fill, in terms of microhardness ratios higher than 80% of the top microhardness values at the 4 mm depth for all LCUs and the 5 mm depth for all LED LCUs [5–7,39,40,43]. Further, Farzad et al. [34] reported that a QTH LCU produced a higher bottom-to-top hardness ratio than LED LCUs when curing a 2 mm thick bleach shade of regular composite resin, while Cardoso et al. [9] found that the Valo multi-peak LCU significantly increased the DC and microhardness in 2 mm bulk-fill composites with additional photoinitiators (e.g., Tetric Bulk Fill) compared to a monowave LCU, while composites containing only CQ did not show differences. These findings suggest that high-translucency materials can adequately cure with lower-energy LCUs, whereas polywave LCUs do not always offer an advantage for all materials.

4.2. Top and Deeper Hardness Measurements

The air-inhibited layer depth range, primarily composed of unreacted monomers, varies from 4 µm to 60 µm and can influence surface hardness due to its less-polymerized nature [2,44,45]. To minimize bias from this layer, microhardness at a 0.5 mm depth was used as the reference for top hardness in this study, as this represents the maximum expected Vickers Hardness Number (VHN). This initial microhardness depth measurement is well below the oxygen-inhibited layer. Previous research by Giorgi et al. [22] and Par et al. [44] has shown that bottom surface hardness can sometimes exceed top surface hardness when unpolished due to a resin-rich layer. By using the 0.5 mm depth as a reference, potential surface irregularities affecting hardness measurements were reduced. Additionally, some bulk-fill composites tested here showed higher microhardness values at different depths than at the 0.5 mm reference, but no significant differences in the microhardness ratios were observed. This was noted in SDR at the 2 and 3 mm depths with Bluephase Style, Valo, and QTH LCUs; in Filtek Bulk Fill and Venus at depths of 2 and 3 mm for all LED LCUs; in Sonicfill at a 2 mm depth for Bluestyle, Demi Ultra, and QTH; in Tetric Evo Ceram Bulk Fill up to a 5 mm depth with Demi Ultra; and in Xtra-Base with the QTH LCU [46]. Ilie and Stark [47] also reported higher subsurface mechanical properties in low-filled resin composites, attributing this to material shrinkage towards the center of the restoration or enhanced polymerization at deeper levels where the overlying material insulates the exothermic reaction.

4.3. Direct and Indirect Methods to Evaluate Degree of Conversion (DC)

The degree of conversion (DC) can be assessed using direct methods such as Fourier-transform infrared (FTIR) spectroscopy [9,43,48] and Raman spectroscopy [8,31], which measure the conversion of carbon double bonds to single bonds in the resin matrix. Indirect methods like the scrape-back length technique according to ISO 4049 [49,50], which has been criticized for overestimating DoC, and microhardness testing in terms of bottom-to-top microhardness ratio [19,51–53] are also widely employed. In the present study, the DoC was evaluated through the bottom-to-top microhardness ratio. Recent studies continue to support the correlation between microhardness and DoC, noting that a bottom-to-top hardness ratio of 0.80 correlates with a DoC of 0.90 for non-bulk-fill composites, as demonstrated by Ferracane [45] and Bouschlicher et al. [54] and confirmed by modern investigations [9,48]. However, it is critical to recognize that raw microhardness values cannot be directly compared across different composites due to variations in filler type, size, and resin matrix composition [43]. The DoC typically shows a more rapid decline with increasing depth compared to microhardness, highlighting the need for appropriate curing protocols [45,52,54]. Tsuzuki et al. [31] compared the DoC of the SDR bulk-fill by a polywave and monowave LCU at a 4 mm depth through Raman spectroscopy; no significant difference was found between the polywave and several monowave LCUs used. The advantage of direct methods is that they give a percentage of reacted double bonds, and the disadvantage is that they can be measured in unreacted and reacted composites, while the microhardness ratio used in this study can be measured at different depths of the same specimen [8,11–13,17,18,48,50,52–58]. The microhardness ratio depicts the deterioration of the mechanical properties of a composite resin at a certain depth compared to the surface and could give some idea about clinical performance. An enhanced DoC was reported when irradiation was extended to 40 s [8,28,31,52,53].

4.4. Adequate Depth of Cure (DoC) Achieved by Most Composites

As already mentioned before, CR is considered adequately cured at a specific depth (DoC) if the bottom-to-top microhardness ratio exceeds 80% [4,32,48]. Studies have consistently shown that bulk-fill composites, such as SurefilSDR and Venus Bulk Fill, achieve clinically acceptable degrees of conversion and hardness when cured with appropriate LED light-curing units (LCUs), even at greater depths [21–24]. Specifically, Alrahlah et al. [20], Bucuta and Ilie [19], and Son et al. [28] confirmed that bulk-fill composites could achieve a bottom-to-top hardness ratio exceeding 80% when cured at depths up to 4 mm using LED LCUs, indicating a sufficient depth of cure. These findings have been corroborated by others as well [29,30]. However, not all studies support these results. Yildirim et al. [11] reported that SDR Plus and SonicFill 2 did not exhibit an acceptable depth of cure when polymerized with a monowave LED following the manufacturer's instructions. On the other hand, Tsuzuki et al. [31], Siagian et al. [32], Conteras et al. [33], and Adams et al. [10] found no significant difference in the degree of conversion of bulk-fill composites when comparing monowave and polywave LCUs. Interestingly, Farzad et al. [34] reported that a quartz–tungsten–halogen (QTH) LCU produced a higher DoC than monowave or polywave LED LCUs in bleach shade regular composites. In our study, all bulk-fill composites met this criterion at a 4 mm depth when cured with all LCUs, except for SonicFill and Tetric EvoCeram Bulk Fill with the Valo LCU, as well as Tetric EvoCeram Bulk Fill and X-tra Base cured with the Bluephase Style. Composites such as SDR, Filtek Bulk Fill, and SonicFill demonstrated an 80% hardness ratio at depths greater than 4 mm. According to Shimokawa [43] the BlueStyle LCU emits 22% of its irradiation in the violet spectrum, and Valo 26%, which could be about 220 mW/cm^2 and 260 mW/cm^2, respectively, in this study. This energy does not help the polymerization process in materials with only CQ as a photoinitiator, so the spectral irradiance in the blue region (absorbed energy that can excite CQ) was 800 mW/cm^2 for Bluephase Style and 740 mw/cm^2 for Valo according to the measured radiant power in this study. Violet light cannot penetrate the composite beyond 2.5 mm [43], and therefore cannot be useful in properly curing composites, such as Tetric EvoCeram, containing alternative photoinitiators like TPO or Ivocerin at a depth of 4 mm. This could be the reason for the decreased DoC for SonicFill and Tetric EvoCeram Bulk Fill with the Valo LCU, as well as for Tetric EvoCeram Bulk Fill and X-tra Base cured with the Bluephase Style, in this study. Maucoski et al. [55] reported that the power output of different LED LCUs can vary up to 60%, and sometimes they do not comply with the manufacturers' information, being lower. For SonicFill, which the manufacturer recommends curing up to 5 mm, our results confirm its adequacy, aligning with recent studies by Moharam et al. [29], Nagi et al. [30], and Son et al. [29], which found similar DoC results under various curing conditions. However, other research, such as that of Yap et al. [56], Zorzin et al. [57], and Jakupovic et al. [58], indicates that some composites may fail to achieve an adequate DoC under certain conditions, emphasizing the importance of selecting the appropriate LCU type and exposure parameters. In the present study, microhardness was measured at a time beyond 24 h, and as a result, higher values due to additional post-curing of the specimens were expected [20]. The 24 h post-curing hardness of bulk-fill composites was reported to be between 9% and 100%, and the materials presenting a low initial DoC presented a higher post-curing DC [59].

4.5. Differences in Light-Curing Units (LCUs) and Depths of Cure (DoCs)

Michaud et al. [60] and Price et al. [61,62] reported that polywave LED LCUs often exhibit non-uniform irradiance profiles at their tips, resulting in inconsistent polymerization depending on the photoinitiator and the orientation of the LCU. In contrast, monowave LED, halogen, and plasma arc LCUs tend to provide more uniform light emissions. The Valo polywave LED LCU, when emitting light of 20 J/cm^2 in total, was calculated to have a radiant emittance transmitted of 15.5 (+/−0.4) J/cm^2 over 420–495 nm and of 4.5 (+/−0.2) J/cm^2 over 380–420 nm [43,44]. Flowable bulk-fill composites, such as SDR, Filtek Bulk Fill, Xtra-Base, and Venus Bulk Fill, are expected to exhibit a higher depth of cure than high-viscosity composites, such as SonicFill and Tetric EvoCeram Bulk Fill. In the present study, the high-viscosity SonicFill and Tetric EvoCeram Bulk Fill did not present 80% of the top hardness at the 4 mm depth when irradiated with the Valo and QTH LCU, respectively. This could be because the QTH LCU emitted light with total energy of 12 J/cm^2, which is much less than the 20 J/cm^2 that the rest of the LCUs emitted. Nevertheless, when SonicFill was irradiated with the Valo LCU, it received 20 J/cm^2 of energy, but only the blue spectra could polymerize it, and thus just 15.5 J/cm^2 of the energy absorbed was able to be useful for polymerization. Tetric EvoCeram Bulk Fill, containing CQ, TPO, and Ivocerin as photoinitiators, did not fulfill the 80% microhardness criterion at the 4 mm depth when irradiated by the polywave LED LCUs, but did when irradiated by QTH or monowave LED LCUs. When the QTH or monowave LED LCU was used for Tetric EvoCeram Bulk Fill, the 80% criterion was fulfilled even for the 5 mm depth. These findings could be attributed to the fact that the violet spectra of light emitted from the polywave LED LCUs were not able to penetrate to the 4 mm depth, but only up to 2.5 mm depth [41,63–66], especially in viscous composites, despite its high light translucency. Nevertheless, QTH LCUs emit light in a broad spectrum, and may adequately cure bulk-fill composites with additional photoinitiators. On the contrary, blue light, emitted by QTH and monowave LED LCUs, was able to penetrate up to the depth of 4 mm or deeper, and was able to adequately cure the Tetric EvoCeram Bulk Fill. The QTH used (Elipar Trilight) delivers a small amount of energy, about 10%, in the 350–420 nm (violet) range, while the Bluephase G2 and Valo deliver 14–24% and 17–19% in this region, respectively [41,63,66]. Therefore, even the QTH LCUs can emit light in the violet spectrum, and this could be the explanation for the adequate polymerization of Tetric Evo Ceram Bulk Fill with the QTH LCU. No advantages of polywave LCUs over monowave ones were reported in other studies either [41,46,61–68]. Monowave LED LCUs like Demi Ultra outperformed polywave LCUs in curing composites such as Tetric EvoCeram Bulk Fill, achieving 80% of the VHK microhardness ratio at greater depths. Flowable composites like SDR and Filtek Bulk Fill showed a better curing depth compared to high-viscosity materials like SonicFill and Tetric EvoCeram Bulk Fill, which struggled to reach 80% hardness at 4 mm with Valo and QTH LCUs due to limited blue light penetration. Mixed results have been reported for monowave versus polywave LCUs. Conteras et al. [33] found no significant difference in the degree of conversion (DC) between monowave and polywave LCUs, but others noted that irradiation time and intensity are critical. Adams et al. [10] found no improvement with quad-spectrum LCUs, while Garoushi et al. [52] reported microhardness drops with high-intensity LCUs. Longer irradiation times led to better curing depths [64], while high irradiance with short exposure proved inadequate [50,69–72]. Overall, monowave LED or QTH LCUs with higher energy and longer exposure times are recommended for optimal bulk-fill composite curing, especially for high-viscosity materials.

4.6. Effect of Composite Composition on Depth of Cure (DoC)

The depth of cure (DoC) is significantly influenced by the composition of the composite, including filler size, shape, loading, and the type and concentration of monomers and photoinitiators used [12–14]. Smaller fillers, like colloidal silica, tend to scatter light more, reducing light penetration and the DoC, while larger fillers or lower filler loading typically allow for deeper light penetration, thereby improving the DoC [28]. In our study, flowable bulk-fill composites such as SDR, Filtek Bulk Fill, and Venus Bulk Fill demonstrated better curing performance than more viscous composites like SonicFill and Tetric EvoCeram Bulk Fill. These findings are consistent with the studies by Jung et al. [70] and Garoushi et al. [52], which also observed enhanced DoC in more translucent, lower-viscosity composites. Generally, our results also showed that the flowable bulk-fill composites tested in this study, including SDR, Filtek Bulk Fill, Xtra-Base, and Venus, achieved a microhardness ratio higher than 80% at a depth of 4 mm for all LCUs and 5 mm for the LED LCUs. The energy absorption by the bulk-fill specimens was over 20 J/cm^2 for all LCUs except for QTH, which delivered 12 J/cm^2. Ilie and Stark [47] suggested that a minimum energy density of 24 J/cm^2 is necessary for properly curing bulk-fill composites to a depth of 4 or 5 mm.

4.7. Impact of Light Energy and Irradiation Time

An energy density of 20 J/cm^2 is generally sufficient for polymerizing bulk-fill composites to a 4 mm depth [47,69]. Adjusting irradiation time and power is crucial; reducing them can compromise the degree of cure (DC) and mechanical properties, while increasing them may improve curing depth but risks overheating and shrinkage stress accumulation [39,40,69]. Optimizing these parameters based on composite type and clinical needs is essential for success. Wang and Wang [8] found that two light-cured bulk-fill composites were under-cured at a 5 mm depth (<80%) when cured with a monowave LCU for 20 s, while dual-cured composites exceeded 80%. Extending the curing time to 40 improved the light-cured materials but did not affect the dual-cured ones, and extending beyond 40 s did not have any significant effect [8,28,31,52,53]. Therefore, the irradiation time used in this study was 20 s for uniformity purposes since it was above the manufacturer's recommendations and the emitting energy was not normalized for each LCU.

Overall, monowave LED LCUs, such as Demi Ultra, provide better light dispersion and effective polymerization for most bulk-fill composites, particularly those with CQ as their primary photoinitiator. Polywave LCUs often do not outperform monowave LEDs in composites with multiple photoinitiators due to limited violet light penetration beyond 2.5 mm in viscous materials [39,41,42,68]. These findings align with the research by Price et al. [39], Fronza et al. [64], Par et al. [46], Rocha et al. [41,66], and Oliveira et al. [42], highlighting the need to select the appropriate LCU and curing protocol based on the composite's properties to optimize outcomes.

4.8. Limitations of This Study and Future Research Initiatives

While our results demonstrate the relative performance of various LCUs and highlight the factors influencing polymerization outcomes, several limitations must be acknowledged to contextualize these findings and guide future research efforts. First, this study included a limited range of LCUs, specifically a halogen unit, a monowave LED, and two polywave LEDs [9,43]. The results apply to the bulk-fill composite resin and LCUs tested. Moreover, this study relied on microhardness as an indirect measure of the degree of conversion (DC), which, while reliable, does not provide a direct quantification of polymerization. Direct methods like Fourier-transform infrared spectroscopy (FTIR) or Raman spectroscopy offer more precise insights into the DC at different depths and should be considered in future studies for a more accurate evaluation [39,43]. Another limitation is the standardized curing times and irradiance levels used for each LCU in this study. Different combinations of these parameters, such as varying exposure times or irradiance levels, could significantly affect polymerization outcomes, particularly for composites with different photoinitiator systems or filler compositions and possessing a variety of shades and opacities [46,53,70–72].

5. Conclusions

Based on the 80% top hardness criterion, the following conclusions can be made: (1) The results revealed significant differences in the microhardness and microhardness ratios among the composites at depths of 4 mm and beyond, depending on the LCU used. (2) Not all light-curing units (LCUs) were effective in adequately polymerizing all bulk-fill composites at a depth of 4 mm or beyond. (3) All bulk-fill composites demonstrated a sufficient depth of cure, as indicated by the microhardness ratio, when polymerized with the QTH or monowave LCUs at a depth of 4 mm; however, this was not the case with the polywave LCUs. (4) All flowable bulk-fill composites achieved a sufficient depth of cure, as indicated by the microhardness ratio, when cured with any of the LCUs at a depth of 4 mm. (5) Overall, the polywave LED LCU did not show a significant advantage in depth of cure, as indicated by their microhardness ratio, compared to the monowave LED LCU when used with bulk-fill composites containing multiple photoinitiators. Clinically, this suggests that to achieve an optimal depth of cure, especially in CRs with various photoinitiators, a monowave LED LCU may be equally effective, simplifying the choice of curing unit in practice. Polywave LED LCUs can be effectively used in regular composite resins with additional photoinitiators, which are cured in increments up to 2 mm. Finally, violet light can effectively penetrate bulk-fill composites up to 2.5 mm.

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