

Systematic Review

Dental Bulk-Fill Resin Composites Polymerization Efficiency: A Systematic Review and Meta-Analysis

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Abstract: Dental Bulk-Fill Composites (BFCs) and Bulk-Fill Flowables (BFFs) were introduced in the market to facilitate efficient bulk filling of cavities up to 5 mm. The aim of this study was to synthesize the literature investigating their polymerization efficiency. A comprehensive search of PubMed and the Cochrane Library from 2010 to January 2019 was performed using the medical subject headings. Screening of the titles, abstracts and full text was performed. Data extraction for relevant information was done on the included studies. Clinically relevant parameters were selected to present the study estimates (meta-analysis) using a random effects model for polymerization efficiency (Degree of Conversion (DC) and Depth of Cure (DoC)). Twenty one studies fulfilled the inclusion criteria and were included in the analysis reporting seven BFCs and nine BFFs. Ten materials reported acceptable DC values of above 55% and ten materials reported adequate DoC values. Most of the stated materials reported adequate DC and DoC values in at least one investigation with BFFs showing higher and more acceptable values compared to packable BFCs. It is suggested that future studies be carried out using a standard methodology following the ISO 4049 standard and manufacturer's instructions to compare results.

Keywords: bulk-fill composite; bulk-fill flowable; polymerization efficiency; degree of conversion; depth of cure



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1. Introduction

Photo-polymerizable Resin-Based Composites (RBCs) have always been preferred as the material of choice by clinicians due to superior esthetics, improved properties, and operator-controlled working time [1–3]. The application process of these materials requires placing the material in increments no greater than 2 mm in thickness in order to ensure proper penetration of the curing light to the deeper parts of the restoration warranting optimum polymerization [4,5]. Additionally, filling cavities in an incremental manner reduces the magnitude of volumetric shrinkage stresses which accompany the polymerization reaction [6,7]. However, the incremental-placement method is time-consuming, technique sensitive, and depending on the clinician's experience may introduce unwanted voids that could weaken the resulting restoration [4,8,9].

Consequently, new light-cure composite formulations were introduced in the market in order to facilitate bulk filling of cavities where the manufacturers claim that these materials can fill up to 5 mm with predictable polymerization efficiency [4] without the need for the incremental technique; hence expediting the restorative procedure [10,11]. These materials, termed Bulk-Fill Composites (BFCs), have different chemistries which facilitate deeper penetration of the radiated energy from light-cure devices. These materials contain more sensitive photoinitiators other than the commonly used camphorquinone initiator used in conventional RBCs. In addition, these materials tend to be more translucent which allows for more light to pass through [12,13]. These modifications would ensure better exposure of the deeper parts of the restoration to the curing light leading to deeper

depth of cure (DoC) and facilitating more conversion of monomers into polymers leading to better degree of conversion (DC).

Further modifications of the filler contents led to the introduction of low viscosity BFCs which can be utilized as cavity liners while maintaining the bulk-fill potential of their high-viscosity counterparts. These Bulk-Fill Flowables (BFFs) have higher resin matrix content which allows for better stress distribution during the polymerization reaction and consequently less overall stress [14,15].

However, polymerization efficiency of BFCs and BFFs must be tested either directly or indirectly to ensure favorable clinical service. Direct methods, such as Fourier-Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy (RS), measure the DC by determining the proportion of the remaining concentration of the aliphatic C=C double bonds in a cured sample relative to the total number of C=C bonds in the uncured material [16,17] which indicates the conversion ratio of double bonds (C=C) into single bonds (C–C) during the propagation phase of the polymerization reaction [18,19]. This is an important parameter in determining the final physical, mechanical, and biological properties of photo-activated resin composites. The DC of resin composites is influenced by the spectral distribution and intensity of the curing light as well as the shade, opacity, and chemical composition of the RBC [20]. It has been established that BFF materials can reach a clinically acceptable DC, although some of them are on the lower limit of ~55% monomer-to-polymer conversion ratio [21]. Indirect methods can be used to judge the polymerization efficiency by determining the DoC using the Scrapping Method (SM) or Microhardness Ratio (MHR) [22–25]. The former assesses the remaining thickness, which is the length of the cylindrical specimen of cured resin composite, after removal of the uncured resin composite with a plastic spatula, divided by two [24]. While the microhardness (Vickers and Knoop) assesses the bottom-to-top hardness ratio [22,24,26].

In the literature, numerous studies explored and compared the polymerization reaction and their results were inconsistent. Thus, it is paramount to examine the current available evidence regarding BFCs and BFFs formulations in relation to their DC and DoC. The primary aim of this study was to synthesize the literature for publications investigating the polymerization efficiency of BFCs and BFFs using all available direct (RS and FTIR) and indirect methods (SM and MHR). Further, we aim to statistically combine the estimates of DC and DoC to provide clinically relevant outcome values for polymerization efficiency.

2. Materials and Methods

This systematic review was done following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [27].

2.1. Search Strategy

A comprehensive search of NCBI (PubMed) and the Cochrane Library from January 2010 to January 2019 was performed. The following medical subject headings (MeSH terms) were used: “polymerization efficiency”, “resin composites”, “bulk fill composites”, “depth of cure” and “degree of conversion”. The following search sequences was applied in both search engines: (1) “polymerization efficiency AND resin composites”, (2) “bulk fill composites AND depth of cure”, (3) “bulk fill composites AND degree of conversion”, (4) “polymerization efficiency OR degree of conversion”. Additionally, references of relevant retrieved reviews were screened for other potential eligible articles.

2.2. Inclusion and Exclusion Criteria

All English language articles were included and the inclusion criteria used were (a) utilize in-vitro methods, (b) studies documenting polymerization efficiency of BFC by measuring selected parameters: DoC or DC, and (c) cavities with a minimum depth of 3 mm. Only studies utilizing in vitro methodology were included due to the difficulty in standardization of the in vivo studies and to reduce the independent variables that affect the outcome of the studies. Studies with a minimum depth of 3 mm were included to

be in line with the objective of using BFCs which is curing beyond the standard 2 mm incremental fill conventional resin composites [4]. All non-English language articles as well as reviews were excluded. Articles investigating different parameters than DC and DoC or reporting values other than the numerical mean were also excluded.

2.3. Study Selection

All retrieved studies were screened by two independent reviewers (R.A.G and N.A.N) for eligibility. Disagreement was resolved by a third reviewer (R.A.A). In the first step of screening, titles were screened, and completely irrelevant studies were excluded. In the second screening stage, abstracts were screened and studies not investigating relevant outcomes (DoC and DC), and in vivo conducted studies were excluded. Subsequently, full-text articles that were potentially acceptable were assessed to identify the final set of eligible articles, as shown in Figure 1.

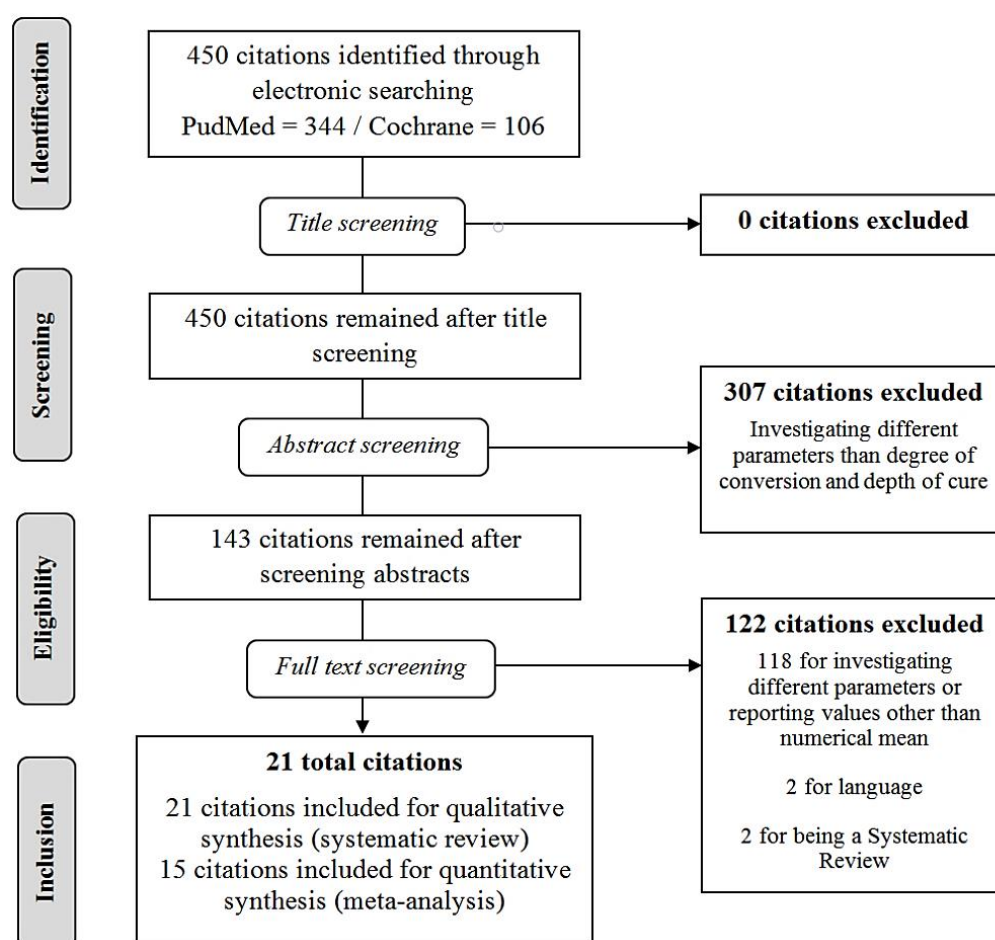


Figure 1. A PRISMA flow chart illustrating the identification process of the included studies in the systematic review and meta-analysis.

2.4. Risk of Bias

The quality of the studies was assessed for risk of bias by N.A.N, using a list of questions that were generated by the authors, assessing the pertinent objective of the study, methodology used (sample size and presence of a control group), and the measured outcomes.

2.5. Data Extraction

From each of the included studies, the following information was extracted: first author name, brand of the composite, type of material (BFC or BFF), sample size, method of measuring polymerization shrinkage, light curing type, light curing time and its intensity.

Different outcomes were extracted for each method. For the SM, the remaining thickness was reported; while for Knoop and Vickers microhardness, microhardness values at the top and at different depths (3, 4, 5, and 6 mm) were recorded to report the bottom-to-top MHR. For RS and FTIR, the DC at the top surface, and at different depths (3 and 4 mm) and at different time points (0, 24 h and 1 week) were recorded.

A customized table was designed for the data extraction. The table was divided into four groups according to different methodology: FTIR, RS, SM, and MHR. The data extraction was done independently by two reviewers (L.M.A and R.A.G), and any discrepancies were solved by consulting other authors (H.M.N or R.A.A). When required information was missing or not clear in the retrieved papers, authors of the relevant papers were contacted.

2.6. Summary Measures

The outcomes of interest were: the DC which was measured directly through RS and FTIR, and the DoC which was measured indirectly via SM and bottom-to-top MHR obtained from Vickers and Knoop microhardness tests. DC values range from 0–100%. DC values \approx 55% and above were considered acceptable according to AlShali and Silikas 2013 [21]. Remaining thickness values of 3.5 mm and above were considered acceptable for the SM according to ISO 4049 as this value is not more than 0.5 mm below the value of at least 4 mm that is stated by the manufacturers of the BFCs and BFFs as the depth with sufficient polymerization [28]. The bottom-to-top MHR values of at least 0.8 were considered as an acceptable ratio according to Poggio et al. 2012 [3].

2.7. Statistical Analyses

Qualitative synthesis of the extracted outcome data was done. The following information was presented for the materials that assessed polymerization sufficiency with the direct methods: material type (BFC or BFF), light cure time (10, 20, 25, 30 and 40 s), DC (mean/SD) for the following time points: immediate cure (at top and 4 mm depth), 24 h (at top and 4 mm depth), 7 days (at 3 and 4 mm depth), and 30 days (at 4 mm depth). For the indirect methods the following parameters were presented; for the SM: light cure time (10, 20, 30 and 40 s), and remaining thickness in mm (mean/SD). While for the microhardness, light cure time (10, 20, 30, 40, and 60 s), hardness number (Vickers or Knoop; mean/SD), and bottom-to-top MHR (ratio), at depths 3, 4, 5, and 6 mm, were presented. Studies reported performing the test immediately, 5 min, or 15 min after light-curing were grouped under zero hours. Additionally, studies with unreported testing time were assumed to have done immediate testing and were placed with the “0 h” category.

To quantitatively summarize the estimates of the different studies, specific fixed parameters were selected according to the ISO standards [28] to present the study estimates. Thus, only samples light cured for the standard 20 s and at depths of 4 mm or more were selected since the main objective of the BF material is to have adequate cure up to 4 or 5mm depth as claimed by the manufacturers. The outcome values that were considered acceptable were indicated. For outcomes which were assessed in 2 studies or more, a meta-analyses was performed. A random effects model was used, as we believed that the estimates were not homogenous, and this was confirmed by the I^2 heterogeneity test, which indicated significant heterogeneity in the summary estimates [29]. The meta-analyses were conducted using Stata 12.2 (StataCorp LP, College Station, TX, USA).

3. Results

3.1. Study Selection

As presented in Figure 1, a total of 450 studies were identified from the search: 344 from PubMed, 106 from the Cochrane Library. From the titles screening, all studies were relevant to our aim and no studies were excluded. From the abstract screening, 307 studies were excluded for investigating different parameters than the DoC and DC. Of the remaining 143 studies which were full text screened, 122 studies were excluded; as 118

have investigated different parameters than the DoC and DC, two reported in non-English language, and two were systematic reviews. Thus, 21 studies which fulfilled the inclusion criteria of our systematic review, were included for final analysis.

3.2. Study Characteristics

Table 1 shows study characteristics of the eligible investigations. All included studies were published between 2013 and 2018, six studies were conducted by multinational collaboration from different countries [30–35]. The sample size of the included studies ranged between three to ten specimens in each study group. The most common type of resin composite reported was Surefil SDR in 17 studies [30–34,36–47]. The studies used four different methods to measure DoC/DC; the most common method was the FTIR method reported in eight studies [31,32,35,36,41,42,47,48] followed by the SM which was reported in five studies [34,37,38,40,41] followed by the Vickers [36,39,42,49] and Knoop [30,33,40,45] Microhardness tests and the RS [43,44,46,50] which were each reported in four different studies. Four studies used multiple measuring methods [36,40–42], while the other 17 studies used a single method each.

3.3. Results of the Individual Studies

Twenty one studies investigated the efficiency of polymerization of BFCs reporting seven BFCs and nine BFFs. Characteristics of the different composite materials are presented in Table 2 including the type of resin matrix, main fillers type, filler load, photo initiator type, and manufacturer's details.

The DC estimates from studies using FTIR and RS are presented in Table 3. The highest reported DC value by the FTIR method was for Venus Bulk-Fill (86.07%) [48] and the lowest reported value was for Tetric N-Ceram Bulk-Fill (24.12%) [47]. The highest reported DC value by the RS was for Surefil SDR (79.0%) [44], and the lowest reported value was for Filtek Bulk-Fill (19.41%) [46].

Table 4 illustrates the remaining thickness values of the studies that used the SM to assess DoC. It also presented the top and bottom microhardness values, and the bottom-to-top MHRs. The highest reported remaining thickness value was for X-tra base (5.68 mm) by Benetti, 2015 [37], and the lowest reported remaining thickness value was for Beautifil Bulk Restorative (2.9 mm) by Yap, 2016 [45]. The highest reported MHR was for Venus Bulk-Fill (1.14) by Czasch, 2013 [36]; and the lowest reported MHR was for SonicFill (0.1) by Alshaafi, 2016 [33].

3.4. Risk of Bias

None of the studies showed a significant risk of bias, thus none were excluded from the meta-analyses.

3.5. Synthesis of Results

Table 5 presents the DC of the studies which used the RS and FTIR methods, but only for the fixed parameters set (20 s light-curing time—at the top, 4 and 6 mm depths, and at 0 and 24 h times as well as irradiance values). For the DC values at 0 h: on the top ranged between 41.9% and 71.46% and at 4 mm depth between 24.12% and 78.8%. At 6 mm, the DC ranged between 36.3% and 65.6%. For the DC values at 24 h: on the top ranged between 46.45% and 74.8% and at 4 mm between 32.71% and 80.07%.

Table 6 illustrates the remaining thickness values for the SM and the MHR values for the fixed parameters set (20 s light-curing time—and 3, 4, 5, and 6 mm depth, as well as irradiance values). The remaining thickness values for the SM ranged between 2.9 and 5.68 mm. The MHR values: at 3 mm ranged between 0.68 and 0.98, at 4 mm between 0.47 and 1.12, at 5 mm between 0.21 and 0.62, and at 6mm between 0.1 and 1.04.

Table 1. Summary of the eligible studies characteristics.

Study	Country	Sample Size	Bulk-Fills							Bulk-Fill Flowables							Analysis Methods				
			Filtek Bulk-Fill	Tetric Evo-Ceram Bulk Fill	Tetric N-Ceram Bulk Fill	SonicFill	Beautiful Bulk Restorative	Aura SDI Bulk Fill	X-Tra Fil	SureFil SDR	Filtek Bulk Flow	Tetric Evo-Flow Bulk Fill	Venus Bulk-Fill	Beautiful Bulk Flowable	EverX Posterior	X-Tra Base	MI Fil	Xenius Base	Fourier-Transform Infrared Spectroscopy	Raman Spectroscopy	Scrapping Method
Czasch, 2013	Germany	6							✓			✓						✓			✓
Benetti, 2013	Denmark	3		✓		✓			✓			✓			✓					✓	
Garoushi, 2013	Finland	5	✓	✓		✓			✓			✓			✓		✓			✓	
El-Damanhoury, 2014	United States *	5		✓				✓	✓			✓									✓
Garcia, 2014	United States	10				✓			✓			✓								✓	✓
Goracci, 2014	Italy	5				✓			✓				✓					✓		✓	
Jang, 2015	South Korea	8			✓				✓			✓									✓
Zorzin, 2015	Germany	5	✓	✓					✓			✓			✓			✓			✓
Marovic, 2015	Croatia *	5							✓			✓			✓			✓			
Li, 2015	Belgium	9		✓					✓	✓				✓					✓		
Ilie, 2015	Germany *	6		✓			✓		✓				✓					✓			
Pongprueksa, 2015	Belgium	10								✓									✓		
Nagi, 2015	Egypt	5		✓				✓													✓
Al-Ahdal, 2015	Germany *	6	✓	✓		✓	✓					✓	✓	✓	✓			✓			
Alshaafi, 2016	Canada *	5		✓		✓			✓												✓
Par, 2016	Croatia	4							✓		✓								✓		
Yap, 2016	Singapore	5			✓		✓		✓				✓	✓							✓
Lempel, 2016	Hungary	5	✓						✓						✓				✓		
Tsujimoto, 2017	Japan *	10	✓	✓			✓		✓	✓			✓							✓	
Gonçalves, 2018	Brazil	5	✓			✓		✓		✓		✓		✓				✓			
Jain, 2018	India	5			✓				✓				✓			✓		✓			

* Multinational studies; country of the corresponding author is presented.

Table 2. Summary of bulk-fill resin composite materials found in the cited publications.

Material	Resin Matrix	Main Fillers	Filler Load (wt %/vol%)	Photoinitiator	Manufacturer
Bulk-Fills					
Filtek Bulk-Fill	AUDMA, UDMA, DDDMA	Silane-treated ceramics, silica, zirconia	77/59	CQ	3M ESPE, Dental Products, Saint Paul, MN, USA
Tetric Evo-Ceram Bulk Fill	Bis-EMA, UDMA, EBPADMA	Barium aluminium silicate glass, ytterbium trifluoride	80/61	CQ, Ivocerin®	Ivoclar Vivadent, Zurich, Switzerland
Tetric N-Ceram Bulk Fill	Bis-GMA, Bis-EMA, UDMA	Barium aluminium silicate glass, ytterbium trifluoride	76/-	CQ, Ivocerin®	Ivoclar Vivadent, Zurich, Switzerland
SonicFill	3-trimethoxysilylpropyl methacrylate, Bis-EMA, Bis-GMA, TEGDMA	Barium, aluminum boron, silicate	84/83	CQ	Kerr Dental, Orange, CA, USA
Beautifil Bulk Restorative	Bis-GMA, UDMA, Bis-MPEPP, TEGDMA	S-PRG fluoroboroaluminosilicate glass	87/75	Not disclosed	Shofu Inc., Kyoto, Japan
Aura SDI bulk fill	Not disclosed	Not disclosed	74/-	Not disclosed	Radii, SDI, Bayswater, Australia
X-tra fil	MMA, Bis-EMA, Bis-GMA, UDMA, TEGDMA	Inorganic fillers	75/58	Not disclosed	Voco, Cuxhaven, Germany
Bulk-Fill Flowables					
SureFil SDR	UDMA, Bis-EMA, TEGDMA	Barium- and strontium alumino-fluoro-silicate glass	68/44	CQ	Dentsply Caulk, Milford, DE, USA
Filtek Bulk Flow	Bis-GMA, UDMA, Bis-EMA	Silane treated ceramic, ytterbium fluoride filler	65/43	CQ	3M ESPE, Dental Products, Saint Paul, MN, USA
Tetric Evo-Flow Bulk Fill	Dimethacrylates, Copolymers	Barium glass, ytterbium trifluoride	68/46	CQ, Ivocerin®	Ivoclar Vivadent, Zurich, Switzerland
Venus Bulk-Fill	UDMA, Bis-EMA	Barium glass, ytterbium trifluoride, silicon dioxide glass	65/38	Not disclosed	Heraeus Kulzer, South Bend, IN, USA
Beautifil Bulk Flowable	Bis-GMA, UDMA, Bis-MPEPP, TEGDMA	S-PRG fluoroboroaluminosilicate glass	73/51	Not disclosed	Shofu Inc., Kyoto, Japan
EverX Posterior	Bis-GMA, TEGDMA, polymethyl methacrylate	Glass fibers, barium borosilicate glass	74/54	CQ	GC Dental Products, Tokyo, Japan
X-tra base	Bis-EMA, UDMA	Inorganic fillers	75/60	Not disclosed	Voco, Cuxhaven, Germany
MI Fil	UDMA, Bis-MEPP, TEGDMA	Silica nanofillers	69/-	Not disclosed	GC Dental Products, Tokyo, Japan
Xenius base	Bis-GMA, PMMA, TEGDMA	Short E-glass fiber filler, barium	74/54	Not disclosed	Stick Tech Ltd., Turku, Finland

AUDMA: aromatic urethane dimethacrylate; Bis-GMA: bisphenolglycidyl methacrylate; Bis-EMA: ethoxylated bisphenol-A dimethacrylate; Bis-MEPP: bisphenol-A-ethoxylat(2)dimethacrylate; Bis-MPEPP: bisphenol A polyethoxy methacrylate; CQ: Camphorquinone; DDDMA: 1,12-dodecane dimethacrylate; ivocerin: dibenzoyl germanium derivative; TEGDMA: tri-ethylene-glycol-dimethacrylate; UDMA: urethane dimethacrylate; wt %: weight percentage; vol.%: volume percentage.

Table 3. Means and standard deviations (in parenthesis) of degree of conversion data depicted from direct methods.

Material	Light Cure Time (sec.)	Raman Spectroscopy							Fourier-Transform Infrared Spectroscopy						References	
		0 h [#]		24 h		7 days		30 days	0 h [#]				24 h			
		top	4 mm	top	4 mm	3 mm	4 mm	4 mm	top	3 mm	4 mm	6 mm	top	4 mm		
Bulk-Fills																
Filtek BF	10	48.63 (0.4) ^														Lempel, 2016
	20	52.26 (0.50) ^														Al-Ahdal, 2015
	25															Gonçalves, 2018
Tetric Evo-Ceram BF	10															Zorzin, 2015
	20								51.0 (1.6)		47.4 (1.6)	41.6 (1.4)	67.45 (6.58)	63.4 (4.37)	Ilie, 2015	
											46.9 (4.53)			54.5 (1.53)	Al-Ahdal, 2015	
	30												52.95 (11.07)	54.63 (3.67)	Zorzin, 2015	
Tetric N-Ceram BF	20								46.3 (1.75)		24.12 (1.08)		52.75 (1.11)	34.13 (1.55)	Jain, 2018	
Sonic Fill	20								71.46 (2.15)		57.95 (4.77)				Goracci, 2014	
											66.6 (4.96)			71.6 (3.98)	Al-Ahdal, 2015	
	25									74.6 (2.5)	63.0 (5.0)				Gonçalves, 2018	
Beautifil Bulk Restorative	20								41.9 (2.3)		40.0 (2.1)	36.3 (1.7)			Ilie, 2015	
											38.9 (4.57)			49.7 (4.98)	Al-Ahdal, 2015	
Aura SDI BF	25									58.9 (4.5)	48.1 (7.9)				Gonçalves, 2018	

Table 3. Cont.

Material	Light Cure Time (sec.)	Raman Spectroscopy							Fourier-Transform Infrared Spectroscopy						References
		0 h #		24 h		7 days		30 days	0 h #				24 h		
		top	4 mm	top	4 mm	3 mm	4 mm	4 mm	top	3 mm	4 mm	6 mm	top	4 mm	
Bulk-Fill Flowables															
SureFil SDR	10								58.9 (2.9)		58.3 (1.7)	57.1 (3.0)			Czasch, 2013
	20		58.0 (2.5)		73.0 (2.0)		79.0 (3.0)	78.5 (2.5)							Par, 2016
				63.04 (0.2) ^	50.05 (0.2) ^										Lempel, 2016
									61.1 (1.5)		59.7 (1.7)	58.2 (1.7)			Czasch, 2013
									70.18 (2.01)		50.36 (2.34)				Goracci, 2014
									61.4 (1.4)		70.0 (0.9)				Marovic, 2015
									55.9 (0.7)		57.0 (0.7)	54.8 (0.6)			Ilie, 2015
													56.53 (10.9)	52.04 (12.45)	Zorzin, 2015
									56.95 (2.56)		39.7 (2.21)		74.81 (1.62)	57.67 (2.82)	Jain, 2018
	30												70.86 (2.09)	72.18 (3.29)	Zorzin, 2015
40								60.4 (3.1)		61.2 (2.1)	60.1 (2.0)			Czasch, 2013	
Filtek BF Flowable	20	66.02 (2.16)	62.08 (2.64)												Pongprueksaa, 2015
													55.9 (1.97)	66.4 (4.6)	Zorzin, 2015
	25									43.4 (5.7)	41.0 (2.5)				Gonçalves, 2018
	30												59.62 (3.22)	69.26 (6.49)	Zorzin, 2015
Tetric EvoFlow BF	20		61.0 (1.0)		76.5 (5.0)		77.5 (6.0)	76.0 (5.0)							Par, 2016

Table 3. Cont.

Material	Light Cure Time (sec.)	Raman Spectroscopy							Fourier-Transform Infrared Spectroscopy						References
		0 h #		24 h		7 days		30 days	0 h #		24 h				
		top	4 mm	top	4 mm	3 mm	4 mm	4 mm	top	3 mm	4 mm	6 mm	top	4 mm	
Venus BF	10								65.0 (1.9)		62.9 (2.3)	62.4 (2.5)			Czasch, 2013
	20								64.9 (1.7)		66.1 (2.8)	65.6 (2.0)			
									66.8 (0.4)		78.8 (1.1)			Marovic, 2015	
												63.46 (9.61)	80.07 (2.76)		
													71.9 (2.00)	Al-Ahdal, 2015	
								52.06 (0.91)		35.41 (3.55)		64.89 (1.79)	56.08 (2.03)		
	25									84.9 (9.8)	86.0 (5.7)			Gonçalves, 2018	
	30												65.37 (4.61)	73.93 (3.26)	Zorzin, 2015
40								64.6 (1.6)		67.92 (1.6)	66.1 (2.8)			Czasch, 2013	
Beautifil Bulk Flowable	20								58.7 (0.9)		57.7 (0.6)	55.0 (0.4)			Ilie, 2015
											56.3 (1.73)			65.7 (1.65)	Al-Ahdal, 2015
Ever-X Posterior	20								54.79 (4.66)		37.95 (2.01)				Goracci, 2014
											54.4 (0.64)			66.2 (2.38)	Al-Ahdal, 2015
	25									76.0 (0.9)	68.2 (2.8)				Gonçalves, 2018
X-tra Base	10			43.14 (0.9) ^	28.77 (1.3) ^										Lempel, 2016
	20			46.45 (1.2) ^	34.01 (0.15) ^										
									59.2 (0.8)		67.5 (0.8)				Marovic, 2015

Table 3. Cont.

Material	Light Cure Time (sec.)	Raman Spectroscopy								Fourier-Transform Infrared Spectroscopy						References	
		0 h #		24 h		7 days		30 days	0 h #				24 h				
		top	4 mm	top	4 mm	3 mm	4 mm	4 mm	top	3 mm	4 mm	6 mm	top	4 mm			
	30									49.4 (1.89)				57.7 (3.14)		Al-Ahdal, 2015	
														65.24 (2.51)		62.53 (3.01)	Zorzin, 2015
														61.48 (3.96)		61.53 (4.0)	
MI Fil	20									44.72 (0.86)		24.67 (1.72)		60.78 (2.34)		39.7 (1.6)	Jain, 2018

^ Digitized by WebPlotDigitizer (software details to be added). # The time at 0 h corresponds to articles reported values after immediate curing, after 5 min, or after 15 min postcuring, or unreported time.

Table 4. Means and standard deviations (in parenthesis) of depth of cure data depicted from indirect methods.

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
Bulk-Fills															
Filtek BF	20	4.64 (0.1) ^													Garoushi, 2013 Tsujimoto, 2017
		3.57 (0.11)													
	30	3.81 (0.09)													
	40	4.14 (0.09)													
Tetric Evo-Ceram BF	10		VHN = 57.00 (1.74)	VHN = 58.69 (0.72)			VHN = 48.12 (3.94)	VHN = 51.81 (1.89)			0.84 *	0.88 *			Nagi, 2015
			VHN = 64.52 (2.45)				VHN = 41.92 (4.46)				0.65				Zorzin, 2015
	20	3.86 (0.07) 3.82 (0.08)													Tsujimoto, 2017 Benetti, 2015

Table 4. Cont.

[illegible]

Table 4. *Cont.*

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
Sonic Fill	20	3.20 (0.1) ^	KHN =	KHN =	KHN =		KHN =	KHN =	KHN =		0.68	0.47	0.21		Garoushi,2013 Garcia, 2014 Goracci, 2014 Benetti, 2015 Alshaafi, 2016
		3.46 (0.08)	72.3	72.4	71.1		48.9	34.0	15.1		(0.05)	(0.04)	(0.02)		
		3.47 (0.03)													
		3.43 (0.07)		KHN =	KHN =		KHN =	KHN =			0.70		0.10		
Beautifil Bulk Restorative	20 30 40	2.9 (0.1)	KHN =				KHN =				0.79 *	-	-		Yap, 2016 Tsujimoto, 2017
		3.42 (0.09)	34.58				27.15								
		3.72 (0.08)	(0.69)				(1.1)								
		4.02 (0.08)													
X-tra Fil	10 20		VHN =	VHN =		VHN =	VHN =			0.96 *	0.96 *			Nagi, 2015 El-Damanhoury, 2014 Nagi, 2015 Alshaafi,2016	
			93.76	93.76		89.89	89.89								
				KHN =			KHN =				0.86				
			59.07			51.20				(0.05)					
		VHN =	VHN =		VHN =	VHN =									
			95.39	95.90		93.87	94.12			0.98 *	0.98 *				
			(0.37)	(0.45)		(0.71)	(0.78)								
			KHN =	KHN =		KHN =	KHN =								
				36.2	36.2		31.8	22.0			0.88		0.61		
				(2.9)	(2.9)		(2.8)	(2.1)							

Table 4. *Cont.*

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
	40		VHN = 88.56 (2.53)	VHN = 93.91 (1.78)			VHN = 90.77 (1.80)	VHN = 91.03 (1.24)			1.02 *	0.97 *			Nagi, 2015
	60		VHN = 92.49 (1.86)	VHN = 92.81 (0.65)			VHN = 89.64 (1.09)	VHN = 91.20 (1.45)			0.97 *	0.98 *			
Bulk-Fill Flowables															
SureFil SDR	10	4.37 (0.25) ^		VHN = 55.1 (2.3)		VHN = 55.1 (2.3)		VHN = 58.2 (4.1)		VHN = 55.4 (3.8)		1.06 *		1.01 *	Czasch, 2013
	20			VHN = 69.1 (3.3)		VHN = 69.1 (3.3)		VHN = 59.8 (2.9)		VHN = 59.0 (3.4)		1.01 *		1.00 *	Garoushi, 2013
				KHN = 29.4 (1.16)	KHN = 29.7 (3.97)	KHN = 31.5 (1.42)		KHN = 21.1 (1.98)	KHN = 19.8 (2.78)	KHN = 19.4 (2.74)		0.72 (0.08)	0.69 (0.18)		Garcia, 2014
															Goracci, 2014
					KHN = 48.53 (2.38)				KHN = 44.27 (2.78)				0.91 (0.06)		El-Damanhoury, 2014
															Benetti, 2015
					VHN = 32.14 (1.42)				VHN = 30.28 (1.73)				0.94		Jang, 2015
					VHN = 39.82 (3.64)				VHN = 38.12 (2.22)				0.96		Zorzin, 2015

Table 4. *Cont.*

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
Filtek Bulk Flow	30	3.6 (0.05)	KHN = 24.24 (0.91)	KHN = 24.24 (0.91)			KHN = 18.84 (0.56)	KHN = 16.04 (0.37)			0.78 *	0.66 *			Yap, 2016
		3.91 (0.09)		KHN = 9.7 (1.3)	KHN = 9.7 (1.3)			KHN = 7.7 (0.5)	KHN = 5.7 (1.1)			0.80		0.59	Alshaafi,2016
								VHN = 36.18 (2.87)	VHN = 35.37 (1.94)			0.99			Tsujimoto, 2017
															Zorzin, 2015
															Tsujimoto, 2017
		4.22 (0.11)		VHN = 59.1 (1.3)	VHN = 59.1 (1.3)			VHN = 59.5 (2.9)	VHN = 58.9 (2.6)			1.01 *		1.00 *	Czasch, 2013
	40	4.41 (0.09)													Tsujimoto, 2017
		20	3.73 (0.08)												Tsujimoto, 2017
Filtek Bulk Flow	30	3.95 (0.06)													
	40			VHN = 40.47 (2.40)				VHN = 36.5 (1.90)				0.90			Zorzin, 2015
		4.24 (0.19)													Tsujimoto, 2017
Venus BF	10	5.01 (0.02)													Garcia, 2014
	20	4.16 (0.75) ^		VHN = 40.7 (4.0)	VHN = 40.7 (4.0)			VHN = 46.5 (4.7)	VHN = 39.1 (2.9)			1.14 *		0.96 *	Czasch, 2013
														Garoushi, 2013	
				VHN = 41.4 (1.5)	VHN = 41.4 (1.5)			VHN = 46.4 (0.9)	VHN = 43.0 (1.4)			1.12 *		1.04 *	Czasch, 2013

Table 4. Cont.

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
	30	5.57 (0.28)	KHN = 21.3 (1.02)	KHN = 23.5 (3.25)	KHN = 23.0 (2.34)		KHN = 16.6 (0.70)	KHN = 15.6 (2.09)	KHN = 13.5 (0.74)		0.78 (0.03)	0.67 (0.10)	0.59 (0.07)		Garcia, 2014
				KHN = 36.60 (0.97)				KHN = 35.53 (1.32)				0.97 (0.02)			El-Damanhoury, 2014
				VHN = 30.55 (1.17)				VHN = 29.95 (1.16)				0.98			Benetti, 2015
				VHN = 34.34 (4.34)				VHN = 29.15 (1.93)				0.85			Jang, 2015
				VHN = 30.64 (2.12)				VHN = 34.41 (2.07)				1.12			Zorzin, 2015
				VHN = 42.7 (4.9)		VHN = 42.7 (4.9)		VHN = 46.4 (1.0)		VHN = 46.0 (1.9)		1.09 *		1.08 *	Czasch, 2013
Beautifil Bulk Flowable	20	3.62 (0.06)													Tsujimoto, 2017
		3.55 (0.03)	KHN = 35.74 (1.17)	KHN = 35.74 (1.17)			KHN = 27.16 (0.64)	KHN = 18.19 (1.9)			0.76 *	0.51 *	-		Yap, 2016
	30	3.86 (0.07)													Tsujimoto, 2017
	40	4.10 (0.07)													
Ever-X Posterior	20	5.29 (0.19)													Goracci, 2014
		3.6 (0.03)	KHN = 33.72 (0.89)	KHN = 33.72 (0.89)	KHN = 33.72 (0.89)		KHN = 24.53 (1.17)	KHN = 21.88 (1.07)	KHN = 19.43 (0.6)		0.73 *	0.65 *	0.58 *		Yap, 2016

Table 4. Cont.

Material	Light Cure Time (sec.)	Scrapping Method (Remaining Thickness; mm)	Microhardness												References
			Top				Bottom				Ratio				
			3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	3 mm	4 mm	5 mm	6 mm	
X-tra Base	20	4.87 (0.3) ^ 5.68 (0.21)													Garoushi, 2013 Benetti, 2015 Zorzini, 2015
	30		VHN = 57.06 (2.76) VHN = 69.86 (9.29)				VHN = 56.96 (3.07) VHN = 67.84 (4.7)				1.00 0.97				
Xenius Base	20	4.58 (0.5) ^													Garoushi,2013

^ Digitized by WebPlotDigitizer (software details to be added); * manual calculation using the equation: microhardness ratio = hardness value at the bottom/hardness value at the top. VHN: Vickers hardness number, KHN: Knoop hardness number.

Table 5. Means and standard deviations (in parenthesis) of degree of conversion data from studies utilizing 20 s light curing protocol at 4 and 6 mm.

Material	Degree of Conversion (%)										n	Light Cure Details (Manufacturer; Irradiance in mW/cm²)	Reference
	0 h \$						24 h						
	Top		4 mm		6 mm		Top		4 mm				
Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)				
Bulk-Fills													
Filtek BF	55.8 (1.06)					58.5 (3.50)				45.6 (20.3–70.8)	6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200 LED.C, Woodpecker, Guilin, China; 1100	Al-Ahdal, 2015 Lempel, 2016
						52.26 (0.5) ^				32.71 (1.2) ^	5		

Table 5. Cont.

Material	Degree of Conversion (%)										n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Reference
	0 h \$					24 h							
	Top		4 mm		6 mm		Top		4 mm				
	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)			
Tetric N-ceram BF	46.3 (1.75)		24.12 (1.08)				52.75 (1.11)		34.13 (1.55)		5	VALO curing light, Ultradent; 1000	Jain, 2018
Tetric Evo- Ceram BF			46.9 (4.53)	47.3 (46.1–48.6)					54.5 (1.53)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015
	51.0 (1.6)		47.4 (1.6)		41.6 (1.4)						6	Ivoclar Vivadent, Schaan, Liechtenstein; NA	Ilie, 2015
Sonic Fill	71.46 (2.15)		57.95 (4.77)	62.3 (53.8–70.8)							5	Demi LED light, Orange, CA, USA; 1100	Goracci, 2014
			66.6 (4.96)						71.6 (3.98)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015
Beautifil Bulk Restora- tive	41.9 (2.3)		40.0 (2.1)	39.8 (38.3–41.3)	36.3 (1.7)						6	Bluephase 20i, Ivoclar Vivadent, Schaan, Liechtenstein; NA	Ilie, 2015
			38.9 (4.57)						49.7 (4.98)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015

Table 5. Cont.

Material	Degree of Conversion (%)										n	Light Cure Details (Manufacturer; Irradiance in mW/cm²)	Reference
	0 h \$					24 h							
	Top		4 mm		6 mm		Top		4 mm				
	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)			
Bulk-Fill Flowables													
Surefil SDR			58.0 (2.5)					73.0 (2.0)			4	Bluephase G2, Ivoclar-Vivadent, Schaan, Liechtenstein; 1185	Par, 2016
	61.4 (1.4)	61.1 (56.5–65.6)	70.0 (0.9)	55.8 (48–63.2)		56.4 (53.1–60.0)		65.6 (55.8–75.3)		58.4 (45.4–71.4)	5	Bluephase G2; Ivoclar Viva- dent, Schaan, Liechtenstein; 1170	Marovic, 2015
	55.9 (0.7)		57.0 (0.7)		54.8 (0.6)						6	Bluephase 20i, Ivoclar Vivadent, Schaan, Liechtenstein; NA	Ilie, 2015
	70.18 (2.01)		50.36 (2.34)								5	Demi LED light, Orange, CA, USA; 1100	Goracci, 2014
	61.1 (1.5)		59.7 (1.7)		58.2 (1.7)						6	Elipar Freelight 2, 3 M ESPE; 1226	Czasch, 2013
								63.04 (0.2) ^		50.05 (0.2) ^	5	LED.C, Woodpecker, Guilin, China; 1100	Lempel, 2016
							56.53 (10.9)		52.04 (12.45)		5	Bluephase20i, Ivoclar-Vivadent; 1200	Zorzin, 2015

Table 5. Cont.

Material	Degree of Conversion (%)										n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Reference	
	0 h \$		4 mm		6 mm		24 h		4 mm					
	Top						Top							
	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)				
Filtek BF flowable	56.95 (2.56)		39.7 (2.21)				74.81 (1.62)		57.67 (2.82)		5	VALO curing light, Ultradent; 1000	Jain, 2018	
	66.02 (2.16)		62.08 (2.64)								10	Bluephase 20i, Vivadent Ivoclar, Schaan, Liechtenstein; 1100	Pongprueksaa, 2015	
							65.9 (1.97)		66.4 (4.6)		5	Bluephase20i, Ivoclar-Vivadent; 1200	Zorzin, 2015	
Venus BF	52.06 (0.91)		35.41 (3.55)				64.89 (1.79)		56.08 (2.03)		5	VALO curing light, Ultradent; 1000	Jain, 2018	
		61.3 (51–71.5)		61.8 (50.8–72.9)				68.1 (60.0–76.3)		69.3 (56.1–82.5)		5	Bluephase G2; Ivoclar Vivadent, Schaan, Liechtenstein; 1170	Marovic, 2015
	66.8 (0.4)		78.8 (1.1)								6	Elipar Freelight 2, 3 M ESPE; 1226	Czasch, 2013	
	64.9 (1.7)		66.1 (2.8)		65.6 (2.0)		73.46 (9.61)		80.07 (2.76)		5	Bluephase20i, Ivoclar-Vivadent; 1200	Zorzin, 2015	
				66.6 (0.89)						71.9 (2.00)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015

Table 5. Cont.

Material	Degree of Conversion (%)										n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Reference
	0 h \$					24 h							
	Top		4 mm		6 mm		Top		4 mm				
	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)	Raw	Summary Estimate (95% CI)			
Beautifil Bulk Flow	58.7 (0.9)	57.3 (53.6–61.0)	57.7 (0.6)	50.7 (40–60.8)	55.0 (0.4)						6	Bluephase 20i, Ivoclar Vivadent, Schaan, Liechtenstein; NA	Ilie, 2015
	54.79 (4.66)		37.95 (2.01)								5	Demi LED light, Orange, CA, USA; 1100	Goracci, 2014
			56.3 (1.73)						65.7 (1.65)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015
Ever-X Posterior			54.4 (0.64)						66.2 (2.38)		6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015
X-tra Base	59.2 (0.8)		67.5 (0.8)	58.5 (40–76.2)				55.8 (37.4–74.2)		51.4 (30–72.3)	5	Bluephase G2; Ivoclar Vivadent, Schaan, Liechtenstein; 1170	Marovic, 2015
							46.45 (1.2) ^		34.01 (0.15) ^		5	LED.C, Woodpecker, Guilin, China; 1100	Lempel, 2016
							65.24 (2.51)		62.53 (3.01)		5	Bluephase20i, Ivoclar-Vivadent; 1200	Zorzin, 2015
				49.4 (1.89)						57.7 (3.14)	6	Elipar S10, 3M ESPE, Seefeld, Germany; 1200	Al-Ahdal, 2015

Table 6. *Cont.*[illegible]

Table 6. Cont.

Material	Scrapping Method				Microhardness Ratio					Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	References			
	Remaining Thickness (mm)	n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Summary Estimate (95% CI)	3 mm	4 mm Raw	Summary Estimate (95% CI)	5 mm	6 mm					
Beautiful Bulk Restorative	3.42 (0.09)	10	Optilux 501, Kerr, Orange, CA, USA; ≥600	3.2 (2.7–3.7)	0.79 *					5	BlueShot LED curing light, Shofu; 700	Tsujimoto, 2017		
	2.9 (0.1)	5	BlueShot LED curing light, Shofu; 700									Yap, 2016		
X-tra Fil					0.88					5	Bluephase 20i, Ivoclar Vivadent; 1202	Alshaafi, 2016		
					0.61									
					0.98 *							5	Elipar S10, 3M ESPE; USA; ≥800	Nagi, 2015
					0.86 (0.05)									
Bulk-Fill Flowables														
Sufefil SDR	3.91 (0.09)	10	Optilux 501, Kerr, Orange, CA, USA; ≥ 600	4.4 (3.7–5.1)	0.8 (0.6–1.0)					10	SmartLite iQ2, Model No. 200, Dentsply Caulk; 800 mW2	Tsujimoto, 2017		
	5.01 (0.03)	10	SmartLite iQ2, Model No. 200, Dentsply Caulk; 800		0.72 (0.08)	0.69 (0.18)	0.62 (0.08)		Garcia, 2014					
	5.35 (0.37)	5	Demi LED light, Orange, CA, USA; 1100									Goracci, 2014		
	4.34 (0.15)	3	Bluephase, Ivoclar Vivadent; 950 ± 50									Benetti, 2015		
	3.6 (0.05)	5	BlueShot LED curing light, Shofu; 700		0.78 *	0.66 *	1.00 *		5			BlueShot LED curing light, Shofu; 700	Yap, 2016	
			1.01 *		6	Elipar Freelight 2, 3 M ESPE; 1226			Czasch, 2013					
			0.80		5	Bluephase 20i, Ivoclar Vivadent; 1202			Alshaafi, 2016					
			0.91 (0.06)		5	Demetron A.1, Kerr/Sybron, Orange, CA, USA; 1000 ± 50			El-Damanhoury, 2014					

Table 6. *Cont.*

Material	Scrapping Method			Microhardness Ratio						References		
	Remaining Thickness (mm)	n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Summary Estimate (95% CI)	3 mm	4 mm Raw	Summary Estimate (95% CI)	5 mm	6 mm		n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)
	4.37 (0.25) ^	3	TC-01, Spring Health Products, USA, 1100		0.94				8	Bluephase, Ivoclar Vivadent; 700	Jang, 2015	
					0.96				5	Bluephase20i, Ivoclar-Vivadent; 1200	Garoushi, 2013 Zorzin, 2015	
Filtek Bulk Flow	3.73 (0.08)	10	Optilux 501, Kerr, Orange, CA, USA; ≥ 600								Tsujimoto, 2017	
					0.81				5	Bluephase20i, Ivoclar-Vivadent; 1200	Zorzin, 2015	
Venus BF	5.01 (0.02)	10	SmartLite iQ2, Model No. 200, Dentsply Caulk, 800	5.0 (4.5–5.6)	0.78 (0.03)	0.67 (0.10)	0.8 (0.5–1.1)	0.59 (0.07)	10	SmartLite iQ2, Model No. 200, Dentsply Caulk; 800	Garcia, 2014	
	5.57 (0.28)	3	Bluephase, Ivoclar Vivadent; 950 ± 50								Benetti, 2015	
					1.12 *				6	Elipar Freelight 2, 3 M ESPE; 1226	Czasch, 2013	
					0.97 (0.02)				5	Demetron A.1, Kerr/Sybron, Orange, CA, USA; 1000 ± 50	El-Damanhoury, 2014	
					0.98				8	Bluephase, Ivoclar Vivadent; 700	Jang, 2015	
					0.85				5	Bluephase20i, Ivoclar-Vivadent; 1200	Garoushi, 2013 Zorzin, 2015	
Beautifil Bulk Flow	3.62 (0.06)	10	Optilux 501, Kerr, Orange, CA, USA; ≥600	3.6 (3.5–3.7)							Tsujimoto, 2017	

Table 6. Cont.

Material	Scrapping Method				Microhardness Ratio						References	
	Remaining Thickness (mm)	n	Light Cure Details (Manufacturer; Irradiance in mW/cm ²)	Summary Estimate (95% CI)	3 mm	4 mm Raw	Summary Estimate (95% CI)	5 mm	6 mm	n		Light Cure Details (Manufacturer; Irradiance in mW/cm ²)
	3.55 (.03)	5	BlueShot LED curing light, Shofu; 700		0.76 *	0.51 *				5	BlueShot LED curing light, Shofu; 700	Yap, 2016
Ever-X Posterior	5.29 (0.19)	5	Demi LED light Orange, CA, USA; 1100	4.4 (2.8–6.1)								Goracci, 2014
	3.6 (0.03)	5	BlueShot LED curing light, Shofu; 700		0.73 *	0.65 *		0.58 *		5	BlueShot LED curing light, Shofu; 700	Yap, 2016
X-tra Base	5.68 (0.21)	3	Bluephase, Ivoclar Vivadent; 950 ± 50	5.3 (4.5–6.1)	1.00					5	Bluephase20i, Ivoclar-Vivadent; 1200	Benetti, 2015
	4.87 (0.3) ^	3	TC-01, Spring Health Products, USA; 1100									Garoushi, 2013
												Zorzin, 2015
Xenius Base	4.58 (0.5) ^	3	TC-01, Spring Health Products, USA; 1100									Garoushi, 2013

Foot Notes: ^ Digitized by WebPlotDigitizer (Rohatgi Ankit. WebPlotDigitizer. Website: <https://automeris.io/WebPlotDigitizer>. Version: 4.3. Access date: July 2020). * manual calculation using the equation: Microhardness ratio = hardness value at the bottom/hardness value at the top. Acceptable remaining thickness (bolded) is 3.5 and above according to ISO standards 4049—Dentistry: Polymer-based restorative materials (2019). Acceptable microhardness ratio (bolded) is 0.8 and above according to Poggio C, Lombardini M, Gaviati S, Chiesa M. Evaluation of Vickers hardness and depth of cure of six composite resins photo-activated with different polymerization methods. J. Conserv. Dent. 2012, 15, 237–241.

Estimates of the DoC, remaining thickness, and MHR for all materials are presented in Figure 2. Summary estimates are presented, when available; and when they were not, individual study estimates are presented.

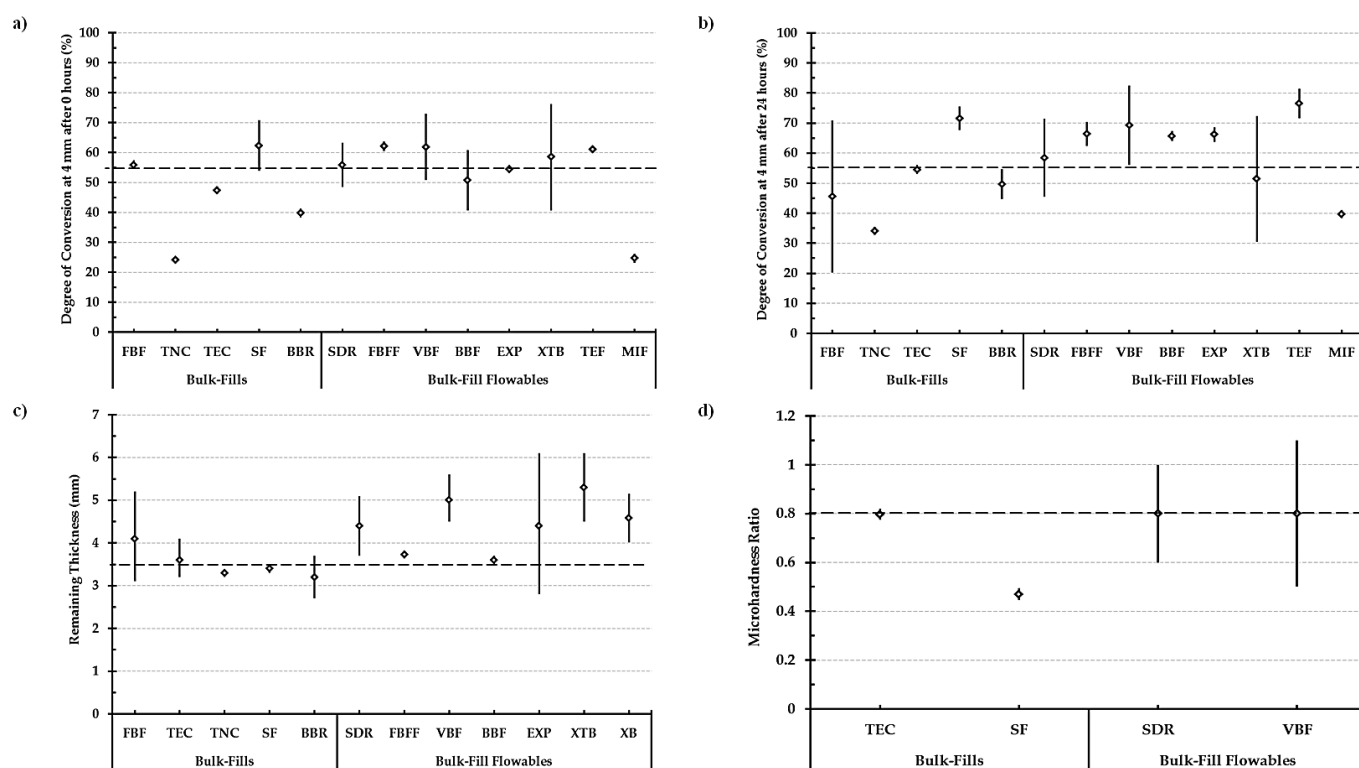


Figure 2. Graphs showing mean values of study parameters from publications reporting means and standard deviations. Summary estimates from relevant meta-analysis were included when performed: (a) degree of conversion at 4 mm (0 h after curing), (b) degree of conversion at 4 mm (24 h after curing), (c) remaining thickness after scrapping method, and (d) microhardness ratio at 4 mm (24 h after curing). Diamonds represent means of individual studies or summary estimates of meta-analysis. Black bars represent 95% CI. Dashed line represents acceptable value for the respective parameter. FBF: Filtek Bulk-Fill, TNC: Tetric N-Ceram Bulk Fill, TEC: Tetric Evo-Ceram Bulk-Fill, SF: Sonic Fill, BBR: Beautifil Bulk Restorative, SDR: SureFil SDR, FBFF: Filtek Bulk-Fill Flowable, VBF: Venus Bulk-Fill, BBF: Beautifil Bulk Flow, EXP: Ever-X Posterior, XTB: X-tra Base, TEF: Tetric Evo-Flow Bulk-Fill, MIF: MI Fil, XB: Xenius Base.

Meta-analyses of the outcome values were performed in 15 of the studies [30–32,34–38,40–42,44–47]; which had estimates for the chosen fixed parameters in two studies or more (Tables 5 and 6).

4. Discussion

Numerous studies in the literature explored and compared the polymerization efficiency either directly or indirectly to ensure favorable clinical service. The results of these studies were inconsistent which makes it crucial to examine the current available evidence regarding BFCs in relation to their DC and DoC. The aim of this study was to investigate the polymerization efficiency of BFCs according to the available evidence in the published literature.

Of the indirect methods studies, SM differs from the MHR method in that the first is a subjective method where inter-operator differences can affect the reliability of the results, while the latter is a quantitative method which makes its results more objective and reliable. In both of these tests, the DC is measured indirectly by measuring the hardness values of the resin composite. On the other hand, the direct methods (RS and FTIR) measure the actual amounts of converted monomers by detecting the ratio between double and single bonds within the polymer chain.

With regards to irradiance values of light curing, the recommended values for BF materials is more than 1000 mW/cm² [30]. Not all studies performed light-curing using devices with the minimal required irradiance [34,37,39,40,45,49]. According to the reported results by the authors, the clinically acceptable values were not related to the recommended light-cure irradiance as some studies reported unacceptable DoC [37,38,40] and DC [32,35,41,42,46,47] values with ≥ 1000 mW/cm² irradiance and some studies reported acceptable DoC [34,37,40,45] values with < 1000 mW/cm² irradiance. Of course, these values can be affected greatly with duration of light-curing exposure.

4.1. Data Extraction and Summary Estimates

Some studies had the results values illustrated on graphs and were not stated in tables neither within the text. These studies were: Lempel 2016 for the DC values [46] and Garouchi 2013 for the remaining thickness values [38]. Still, the values were extracted from the graphs using Web digitizer software [51]. Furthermore, some studies did not report the MHR and only reported the top and bottom microhardness values. These studies were Nagi 2015; Yap, 2016 and Czasch, 2013 [36,45,49]. In these instances, MHRs were calculated manually from the reported top and bottom values of these investigations. In the studies with manually calculated MHRs, the standard deviations of the mean MHRs could not be calculated. Other studies reported the mean MHRs without the standard deviations and these studies were Alshaafi 2016; Jang, 2015 and Zorzin, 2015 [33,39,42]. The authors were contacted for the missing information; however, neither SD values nor raw data were obtained. Thus, these studies were excluded from the meta-analyses while been considered for qualitative analysis.

Summary estimates of the DC results were calculated for materials that were assessed in more than one study. While materials assessed in one study, only the study estimate was presented. Materials where data extraction was done from a single study were Filtek Bulk-Fill (at 0 h), Tetric N-Ceram Bulk Fill, Tetric Evo-Ceram Bulk-Fill (at top and 6 mm depths), Sonic Fill (at top), Beautifil Bulk Restorative (at top, 6 mm depth at 0 h, and 4 mm depth at 24 h), Filtek Bulk-Fill Flowable, Venus Bulk-Fill (at 6 mm depth), Beautifil Bulk Flow (at 6 mm depth), X-tra base (at top at 0 h), Tetric Evo-Flow Bulk-Fill, and MI Fil. Not all materials were tested at the two time points (0 and 24 h) and not all materials were tested at all depths (top, 4 mm and 6 mm). The only two materials which have DC values at all time points and depths are SureFill SDR and Venus Bulk-Fill.

4.2. Degree of Conversion Data

From the DC data in Table 5, it was noticed that some materials did not have an acceptable DC values even at the top surface: Filtek bulk-fill (24 h), Tetric N-Ceram bulk fill (0 and 24 h), Tetric Evo Ceram bulk-fill (0 and 24 h), Beautifil Bulk restorative (0 and 24 h), and MI Fil (0 h and 24 h at 4 mm). Of these materials, only one reported acceptable top surface DC value after 24 h (MI Fil). It was also noticed that the only regular BFC with acceptable DC values at all depths and time points is Sonic Fill. On the other hand, values reported by BFFs (except X-tra Base and MI Fill) were acceptable at almost all depths and time points.

Upon analyzing the DC values comparing the 0 h and 24 h data, it was noticed that some studies reported a lower DC value at 24 h than at 0 h, which was not in accordance with scientific knowledge that the polymerization process continues after light curing [52,53], thus expecting higher DC values with time. This reduction in the DC values with time is considered small and insignificant at the top surface for Filtek Bulk-Fill Flowable and X-tra Base, but is considered significant at the 4 mm depth values for X-tra base and Regular Filtek Bulk-fill where the values becomes unacceptable after 24 h. The latter might be explained by the fact that the 24 h values for X-tra base and Regular Filtek Bulk-fill were calculated as summary estimates from multiple studies who reported significantly different values.

Some materials were associated with higher DC values at increasing depths which was not in accordance with the scientific knowledge that deeper surfaces receive less curing light intensity. SureFil SDR at 0 h showed the highest DC value at the top (61.1%) but the 6 mm depth value (56.4%) was slightly higher than the 4 mm depth value (55.8%). Beautifil Bulk Flow showed the same observation with the highest DC value at the top (57.3%) but the 6 mm depth value (55.0%) was significantly higher than the none acceptable 4 mm depth value (50.7%). Venus Bulk-Fill reported the similar observation at 0 h with the highest DC values at 6mm depth (65.6%) then at 4 mm depth (61.8%) and then at the top (61.3%). Venus Bulk-Fill reported a DC value at 4 mm depth (69.3%) higher than at the top (68.1%) at 24 h. Filtek Bulk-Fill Flowable reported a slightly higher value at the 4mm depth (66.4%) than the top surface (65.9%) at 24 h. This can be explained because some results were calculated as summary estimates from multiple studies reporting significantly different values. For results from single studies, this observation maybe caused by the type of background on which the materials were light cured against and the possibility of a reflective surface being used on the base of mold [31,32,36,42]. Light curing on reflective surfaces might contribute to increasing the DC at the bottom surface since the deeper layers will receive curing light from both the original and the reflected light.

From the analysis of these data, it was found that the BFFs resin composites performed better than the regular BFCs with more acceptable DC values at all time points and depths. This could be explained by the lower filler content which allows for better penetration of light at deeper depths in addition to the higher degree of conversion values at the top surface due to higher ratio of the resin to filler [54].

Among the 21 studies found, one study did not follow the protocol for DC. Li et al., 2015 [43] reported the curing profile of four BFCs (everX Posterior, Filtek Bulk Fill Flowable, SDR, and Tetric EvoCeram Bulk Fill) using RS. The authors found that ever-X Posterior and Filtek Bulk Fill Flowable were effectively cured with DC equal to at least 72% (90% of the mean maximum DC) at depths of 5.47 and 7.84 mm respectively. SDR was effectively cured with DC equal to at least 69% (90% of the mean maximum DC) at a depth of 9.45 mm. Tetric EvoCeram Bulk Fill was effectively cured with DC equal to at least 64% (90% of the mean maximum DC) at a depth of 3.14 mm. Three BFCs in this study, can be compared to the findings of the extracted data from the acceptable studies in this systematic review but none of them had consistent findings as the effective DC reported by Li et al. 2015 were at deeper depths compared to the ones reported by the other studies [43]. One explanation could be that the unreported light curing distance in the included studies which was tested in the paper by Li and collaborators who concluded that the light-cure position has less critical effect on the BFCs' DC compared to conventional RBC [43]. Other investigator-dependent and technical variables (e.g., light cure intensity and resin composite shade) can add up to the light curing distance and might result in reported variation in DC values and DoC.

4.3. Depth of Cure Data

DoC results for the studies with the fixed parameters were extracted from the acceptable values and the summary estimates of the meta-analysis were calculated for the materials with more than one study results. Materials where their data were extracted from a single study only for the SM were Tetric N-Ceram Bulk-Fill, Filtek Bulk Flow and Xenius base. For the MHR, due to the missing standard deviation values in several studies [33,36,39,42,45,49]; summary estimate values could only be calculated for materials with at least two studies having the mean and standard deviation values. The only two materials we were able to have a summary estimate for from two studies for each are SureFil SDR and Venus Bulk-Fill both at 4 mm depth (Garcia, 2014 and El-Damanny, 2014) [30,40] and the rest of the materials had either single study (Tetric Evo-Ceram Bulk-Fill at 3 and 6 mm, SonicFill at 6 mm, Beautifil Bulk Restorative, X-tra fil at 3 and 6 mm, SureFil SDR at 5 mm, Filtek Bulk Flow, Venus Bulk-Fill at 3, 5, and 6 mm, Beautifil Bulk Flow, Ever-X Posterior and X-tra base) or more than one study that could not calculate summary estimates for them due to missing standard deviation (Tetric Evo-Ceram Bulk-Fill at 4 mm, Tetric

N-Ceram Bulk-Fill at 4 mm, SonicFill at 4 mm, X-tra fil at 4 mm, and SureFil SDR at 3 and 6 mm).

For the SM, all BFF materials had acceptable values with each single study and with the summary estimates. On the other hand, only two regular BFCs had acceptable values: Filtek Bulk-Fill and Tetric Evo-Ceram Bulk-Fill while Tetric N-Ceram Bulk-Fill, Sonic Fill and Beautifil Bulk Restorative had unacceptable values with each single study and with the summary estimates but the numbers were close to the acceptable value (Figure 2c).

For the MHR, all of the listed materials have reported MHRs at 3 mm depth except Filtek Bulk Flow and X-tra base. Of these materials only two reported acceptable MHRs at 3 mm depth (Tetric Evo-Ceram Bulk-Fill and X-tra fil). At 4 mm depth all materials reported MHR except Beautifil Bulk Restorative. If only data with SD together with the summary estimates were considered, materials with acceptable MHRs would be: Tetric Evo-Ceram Bulk-Fill, X-tra fil, SureFil SDR and Venus Bulk-Fill. If we considered numbers without SD, it will not be possible to reach a consensus with some materials on whether we consider the reported MHR values acceptable or not. This is because studies' results are not consistent and both acceptable and unacceptable values were reported for the same material of Tetric Evo-Ceram Bulk-Fill, SureFil SDR and Venus Bulk-Fill. The rest of the materials had either consistent findings or were reported by a single study and the materials with acceptable values were X-tra fil and X-tra base. At 5 mm depth, only four materials reported MHRs from single studies and they all had unacceptable values. These materials were SonicFill, SureFil SDR, Venus Bulk-Fill and Ever-X Posterior. While, at 6 mm depth, only five materials reported MHRs four of them were reported from single studies of which Venus Bulk-fill was the only material with acceptable value and SureFil SDR reported MHRs from two studies with an acceptable value by one study [36] and unacceptable value by another study [33]. It is clear from the MHR values that increasing the depth reduced the values but more homogenous studies reporting the required data with SD values at each depth are needed to be able to reach a more solid conclusion.

4.4. Strengths and Limitations

This systematic review has several strengths; it is the first investigation compiling the results from the four methods used to assess polymerization efficiency. Further, standardized outcomes were presented in a concise manner corresponding to the relevant clinical procedure allowing for meaningful statistical synthesis and interpretation of the results. Another strength is that when missing data were encountered, authors were contacted for the relevant data, a dedicated software was used to depict values from figures, or manually calculated by the investigators. Lastly, a rigorous methodology was utilized where two independent reviewers performed all steps of the review which were then overseen by all authors.

Although within our search, a recent systematic review by Lima and collaborators [55] was identified, several key differences between that article compared to the current investigation can be identified. First, in the current investigation, papers published until January 2019 were included and analyzed, which is one and half years after the included search timeframe of the systematic review by Lima and colleagues [55]. Given the rapid advancement in BF composite formulations, the inclusion of recent publications is beneficiary to the researchers and clinicians in order to guide future research efforts and clinical protocols. Additionally, all tests denoting DC either directly or indirectly were included which were complemented by a meta-analysis with heterogeneity assessment. Furthermore, in the current systematic review, parameters were standardized in order to facilitate combining summary estimates into a meta-analysis which gives more optimum quantitative analysis of the data. Lastly, the tables of the current investigation collected and processed the data reported in the studies in an easy to follow manner enabling easier visualization means and standard deviations for each material and testing method reported by each cited paper.

Several factors could have influenced our meta-analyses summary estimates; the number of studies assessing each type of material was relatively small, and there was

marked statistical heterogeneity between the studies. However, heterogeneity estimates are not accurate when the number of studies assessed is small [56]. Furthermore, given the controlled environment in laboratory studies, and that we fixed certain parameters (depth and light curing time) for estimates that were statistically synthesized, and given that a random effects model was used; we believe that these factors make our summary estimates interpretable. Furthermore, the tool used for quality assessment was not validated, as we preferred to use a list of questions that were tailored to our research inquiry. Still, we believe that risk of bias would not be a major concern as all the studies included are in vitro studies which are done in a controlled laboratory environments following previously published well known methodological protocols [22,24,26]. Additionally, all outcomes were assessed objectively using numerical values output from relevant devices.

5. Conclusions

From the above analysis of the data from the reported and selected studies, it is evident that not all reported BFCs showed results that are in accordance with their manufacturer's claims, though there is not enough evidence to reach a solid conclusion. It was also evident that BFFs have higher and more acceptable DoC and DC values compared to regular BFCs. There was no direct relation found between the light-cure irradiance and the outcome. Increasing depth was clearly affecting the outcome and reducing the efficiency of polymerization for most of the data and other data with more DoC at the bottom surface could be the matter of the type of background against which the materials were light cured which can be investigated in future studies. Many limitations were found that affected the decision and resulted in lack of strong evidence to reach consensus. These limitations were the lack of homogenous studies that measured the DoC and/or DC at standard time points, depths, light-curing irradiance, and light curing times. Additionally, the missing data for sufficient statistical analysis and they were not available after contacting the authors. It is suggested that future studies be carried out using a standard methodology following the ISO 4049 standard and manufacturer's instructions regarding the curing time and irradiance and reporting complete data at all time points and depths ensuring stronger evidence with increased potential for reaching consensus. In addition, researchers can refer to the work by Ferracane, Ilie, and collaborators for recent testing guidance [57,58].

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