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REVIEW ARTICLE

Depth of cure of bulk fill resin composites: A systematic review

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ABSTRACT

Objective: To evaluate scientific evidence regarding depth of cure of bulk-fill resin composites (BFRCs) and related factors.

Material and Methods: PubMed/Medline, Embase, Scopus, and ISI Web of Science databases were accessed from October 2016 to May 2017. Investigations published in English language, assessing depth of cure of BFRCs by microhardness test and/or degree of conversion (DC) were included. Studies using exclusively ISO 4049, employing specimens deepness less than 4 mm, as well as those not reporting exposure time and/or irradiance from light curing units (LCUs) were excluded.

Results: In total, 742 studies were found from which 33 were included. From 21 studies evaluating BFRCs microhardness, 10 showed acceptable bottom/top ratios (≥0.8) for all tested materials. However, material-dependent results and non-satisfactory bottom/top microhardness ratios (<0.8) were reported in 9 and 2 investigations, respectively. From 19 studies that assessed DC, 11 showed acceptable results (≥50%) for all tested BFRCs, while 8 studies reported material-dependent outcomes. Overall, irradiance from LCUs ranged from 650 to 1330 mW/cm^2 and exposure time from 5 to 60 seconds. Favorable depth of cure results were observed with the use of LCUs emitting irradiance ≥1000 mW/cm^2 and exposure times ≥20 seconds.

Conclusions: High depth of cure rates by BFRCs, depends on some factors as material, irradiance and exposure time. Polywave LCUs were useful but not essential on polymerizing alternative photoinitiator-containing BFRC.

Clinical Significance: LED curing devices (polywave or monowave) displaying an irradiance ≥1000 mW/cm^2 and 20 seconds of exposure time are imperative to accomplish successful polymerization of most BFRCs.

KEYWORDS
bulk-fill resin composite, degree of conversion, depth of cure, microhardness, review

1 | INTRODUCTION

Bulk-fill resin composites (BFRCs) were recently introduced, claiming capability of being employed as a bulk restorative material when performing direct restorations. This brings the possibility to build up increments up to 4 or 5 mm, while decreasing the typical problems regarding depth of cure and polymerization contraction showed by conventional resin composites when used in these same conditions.[1,2] Manufacturers have explored different strategies to improve the polymerization depth on BFRCs. One approach involves the use of alternative and more reactive photoinitiators and employment of reduced filler content besides increasing its size which enhances material translucency.[3,4] On the other hand, to reduce polymerization shrinkage stress, some chemical modifications have been made to monomers composing BFRCs, such as increasing monomers molecular weight, addition of novel stress-relieving monomers, and incorporation of methacrylate monomers containing a third reactive site.[1,2]

Two main categories regarding BFRCs' viscosity are available: high viscosity and flowable. The first one may be used to fill the whole cavity and sculpt occlusal surface simultaneously. Conversely, flowable BFRCs are indicated to fill most part of the cavity as dentin replacement and the remaining area, including occlusal anatomy, is completed using a conventional or high-viscosity BFRC.[4] Additionally, there is an alternative delivery system that uses ultrasonic waves to modify viscosity of specific bulk-fill materials such as Sonic™ fill (Kerr Corporation) and Sonic™ fill 2 (Kerr Corporation).[5] From a clinical perspective, technique simplicity offered by BFRCs arouses great interest due to reduction in chair-time and operator sensitivity, since incremental technique is no longer imperative for direct restorations' procedure.[6] However, some issues about this simplified restorative sequence have been questioned such as polymerization effectiveness through thick increments as recommended by manufacturers. Problems in this regard may decrease mechanical and biocompatibility properties, while increasing risk of post-operative sensitivity and early restoration failure.[7,8] Due to the fact that clinical use of BFRCs is still incipient and long-term clinical trials are extremely restricted, the confirmation of its effectiveness and consequent indication as a substitute for conventional resin composites is still pendent.[9] Nonetheless, the number of in vitro studies regarding micromechanical performance and light transmittance on BFRCs has increased exponentially in the last years.[10–13] On this regard, several studies have reported acceptable depth of cure at 4 mm, confirming manufacturers recommendations.[10,14,15] Conversely, other investigations have related that some BFRCs present adequate polymerization but only as far as 2 or 3 mm depth.[11,16] Under these conflicting findings, it is not possible to ensure that all commercially available BFRCs can be satisfactorily cured under the same conditions.

It is widely known that factors such as irradiance emitted by light curing units (LCUs) and exposure time delivered to composite material, play an important role on the polymerization quality and further success of resin composite restorations.[17,18] The synergism between both factors will determine the amount of energy reaching the restorative material. On this regard, 16 J/cm^2 has been considered as the adequate quantity of energy for curing up to 2 mm increments of conventional resin composites.[19] Considering that a greater volume of material is employed during restorative procedures, specific minimum dose required to produce an admissible polymerization of BFRCs (placed following manufacturer recommended thickness) is still unclear.[10,20–23] Moreover, in the particular case of those BFRCs added with alternative photoinitiators, polywave LCUs (equipped with blue and violet LEDs) are recommended, in order to match the correct wavelength at which those photoinitiators are excited.[24] Nonetheless, until now no consensus exists about the real impact of these devices on polymerization quality or depth of cure of such materials.

In light of all these issues, concern about lack of homogeneity derived from some current available information regarding depth of cure of BFRCs, is still patent. Additionally, some questions about the effect of modifications in some clinical parameters associated to BFRCs' polymerization, remained unanswered. Hence, it is the purpose of the present systematic review, to evaluate available scientific evidence regarding depth of cure of BFRCs and related factors.

2 | MATERIALS AND METHODS

This systematic review was conducted in accordance to PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).[25] In addition, methodological details were previously registered on PROSPERO (International prospective register of systematic reviews), receiving the protocol number CRD42017059363, available from http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42017059363. The associated research question set for the development of this study was: Do BFRCs reach adequate polymerization at the bottom of 4 mm-thick single-increments?

2.1 | Selection criteria

2.1.1 | Inclusion criteria

All studies assessing depth of cure of 4 mm increments made using flowable and/or high-viscosity BFRCs (compared with conventional resin composites or only between BFRCs) were included. No restrictions were defined regarding methods used by each work to evaluate microhardness (Vickers or Knoop) or degree of conversion (Raman or Fourier Transform Infrared Spectroscopy [FTIR]).

2.1.2 | Exclusion criteria

Studies not published in English language as well as those evaluating depth of cure exclusively by ISO 4049 were excluded. Articles assessing microhardness or degree of conversion only at bottom or top surfaces of the evaluated specimens, and those omitting exposure time and/or irradiance delivered by the LCU employed, were also removed from the preliminary consideration list. Reports that compared exclusively the effectiveness of different polymerization modes (normal, soft start, pulse, high intensity, etc) or LCU types, were eliminated. In addition, editor's letter, comprehensive reviews, and congress abstract were not included on the qualitative synthesis of the current review.

2.2 | Search strategy

PubMed/Medline, Embase, Scopus, and ISI web of science databases were accessed in October of 2016, setting no limit on publication year to find relevant in vitro studies that aimed to evaluate depth of cure of BFRCs (Last update in May of 2017). Two of the authors (R.W.L and M.P.M) who were previously standardized in database searching, undertook systematic searches. The following Medical Subject Headings (MeSH) or "text words" were used: "Bulk fill resin composite," "Polymerization," "Depth of cure," "Microhardness," and "Degree of conversion." The following searches were conducted on each database: (1) ["Bulk fill resin composite AND polymerization"], (2) ["Bulk fill resin composite AND depth of cure"], (3) ["Bulk fill resin composite AND Microhardness"], and (4) ["Bulk fill resin composite AND Degree of conversion"] using advanced option. Additionally, reference lists from selected studies were read in detail to identify other possible reports meeting inclusion criteria. Finally, electronic searches filtered by author/coauthor name were conducted, taking into consideration that "Ilie N" published the greatest number of studies regarding this topic.

2.3 | Study selection

After identification process on four databases, titles were systematically organized in spreadsheets from Microsoft Excel® (Microsoft Corporation, Redmond, Washington, USA) and screened to exclude repeated results. All titles and abstracts were checked in detail and categorized in accordance to the defined selection criteria. Categorization process was conducted independently by two authors (R.W.L and M.P.M) and disagreements were discussed with other authors (C.M.T and M.F.G). Potentially eligible articles were selected for full-text reading and data extraction was performed.

2.4 | Data extraction

Three authors (R.W.L, M.P.M and C.M.T) used a collection form to extract the most important methodological data from included studies. Main data were author name, publication year, type of BFRC evaluated (flowable and/or high-viscosity), commercial reference from LCU (model and brand), type of LCU (monowave/polywave), irradiance (mW/cm^2), exposure time (seconds), and methodology (microhardness test or degree of conversion assessment). In addition, depth of cure results were categorized as follows: acceptable (all tested BFRCs achieved acceptable values), non-acceptable (none of the evaluated materials was properly cured at 4 mm depth), and material-dependent (some BFRCs reached acceptable depth of cure but other did not). A bottom/top ratio ≥0.8 (for microhardness evaluation),[26,27] and a degree of conversion (DC ≥ 50%[28]) were considered as acceptable.

Additionally, bottom/top hardness ratios and degree of conversion of BFRCs were directly extracted (or calculated) from studies that used 20 seconds as exposure time. Later, data were grouped and presented in two scatter charts, showing density and results distribution according to previously established limits. In addition, the number of studies reporting acceptable bottom/top hardness ratios and degree of conversion of each BFRC polymerized for 20 seconds were graphically presented according to LCU used (monowave or polywave).

2.5 | Risk of bias assessment

The risk of bias was evaluated by three authors (C.M.T, M.P.M, and F.M.G) using an adapted instrument previously employed in systematic reviews of in vitro studies regarding bond strength of dental materials.[29,30] Aspects such as randomization, sample size calculation, comparable groups, detailed information regarding measurements, proper statistical analysis, adherence to manufacturer's instructions, single, and/or blinded operator among included studies, were judged with this instrument. If each specific item was considered as positive by authors, it received "Yes" but if not mentioned in the methodology or discussion section, a "No" was assigned. Finally, the risk of bias was established based on the number of "Yes" obtained for each specific study, considering the following ranges: from 1 to 3 (high risk of bias), 4 to 5 (medium risk), and 6 to 8 (low risk).

2.6 | Data analysis

Important methodological heterogeneity was found among included evidence, especially in terms of tested materials, types, and irradiance from LCUs which made it inappropriate to carry out a meta-analysis. Nonetheless, a qualitative and detailed synthesis was conducted based on the outcomes and data extracted from studies that met the inclusion criteria.

3 | RESULTS

3.1 | Search and study selection

Figure 1 specifies identification, screening, eligibility, and inclusion process of studies, according to PRISMA guidelines. Database searching resulted in 740 primary studies, from which 501 were eliminated due to duplication. During screening process, 178 reports were excluded after reading title and abstract. Later, 61 potentially eligible studies were read in detail in PDF format from which 30 were excluded according to criteria presented in Figure 1. After reading reference list from included studies, other potentially eligible studies were identified. Also, by additional electronic searches using "text words," another in vitro investigation that met inclusion criteria was found. Non-extra articles were found by supplementary searches filtered by key author/coauthor name. In total, 33 studies were considered for the qualitative synthesis of the current systematic review.

3.2 | Study characteristics

Main methodological aspects and outcomes from included reports are shown in Table 1. They were published from 2013 to 2017 and "Ilie N" resulted as the author who published the greater number of articles about this issue. Surefil SDR Flow (Dentsply) (n = 25) followed by Tetric EvoCeram Bulk Fill/Tetric N-Ceram Bulk Fill (Ivoclar Vivadent) (n = 19) and Venus Bulk Fill (Heraeus Kulzer) (n = 16) were identified as the most tested BFRCs among included studies. The polywave, Bluephase (Ivoclar Vivadent) and monowave, Elipar S10 (3M/ESPE) devices were the most used LCUs among selected works. Regarding light curing parameters, reported irradiance values emitted by LCUs ranged between 650 and 1330 mW/cm^2. Minimum and maximum exposure time reported among studies was 5 and 60 seconds, respectively. Depth of cure of BFRCs was assessed by hardness tests (n = 14 studies), degree of conversion assessment (n = 12 studies), and both methodologies (n = 7 studies).

3.3 | Risk of bias assessment

Table 2 specifies each item evaluated in individual articles and final decision on risk of bias. From 33 studies included in this systematic review, 20 were classified as having high risk of bias while 13 studies had medium risk. Randomization, sample size calculation, single

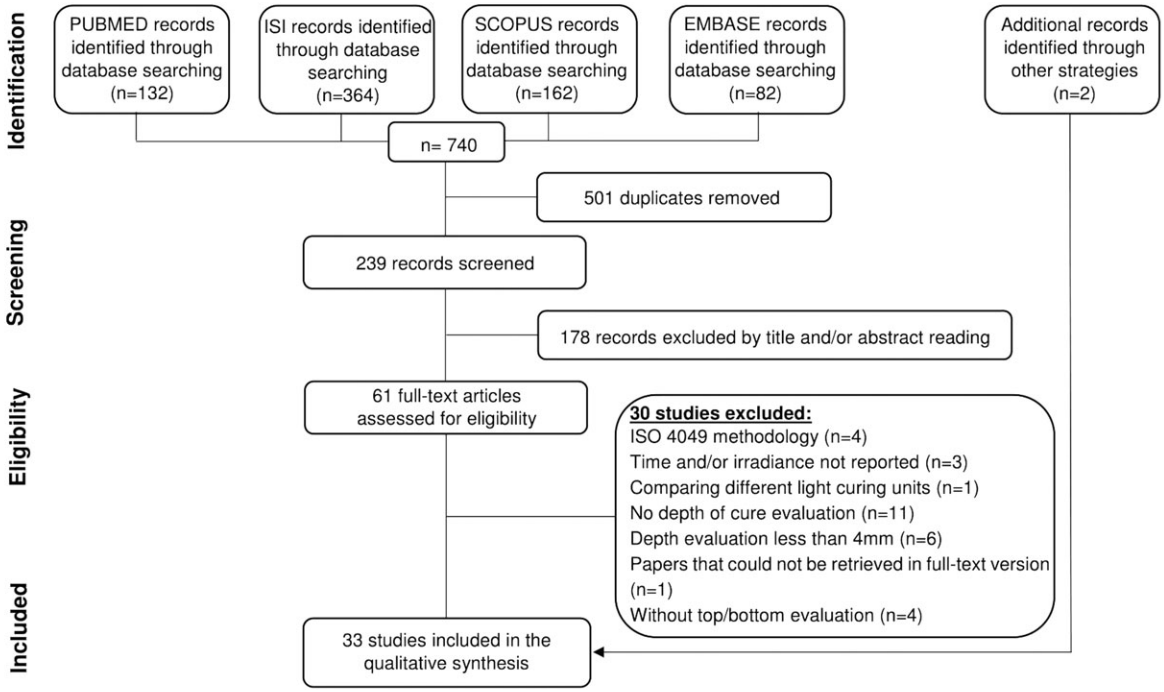

FIGURE 1 Diagram summarizing identification and selection process (PRISMA format)

operator, and operator blinded were the most non-reported items in the methodological design of studies.

3.4 | Synthesis of results

Overall, from 21 studies that assessed BFRCs microhardness, 10 reported acceptable bottom/top hardness ratios (≥0.8) for all materials[10,14,20,21,23,31–35] whereas 9 studies showed material-dependent outcomes.[22,36–43] Conversely, only 2 investigations revealed non-acceptable bottom/top hardness ratio (<0.8) for all BFRCs tested.[11,16] Regarding DC results (Raman/FTIR analysis), 11 studies reported acceptable values (≥50%) for all BFRCs[10,15,20,34,43–49] while eight studies showed material-dependent results.[35,42,43,50–54]

Figure 2 shows bottom/top hardness ratio of BFRCs cured for 20 seconds (independently of LCU type and irradiance). Most studies reported acceptable values for most materials, especially for Filtek Bulk Fill Flow (3M/ESPE), Surefil SDR Flow (Dentsply), Venus Bulk Fill (Heraeus-Kulzer), and Xtra Fill (Voco GmbH) which also revealed more consistent outcomes among studies. Nonetheless, a greater variability in bottom/top hardness ratio was observed in evidence assessing Sonic™ fill (Kerr Corporation) and Tetric EvoCeram Bulk Fill/Tetric N-Ceram Bulk Fill (Ivoclar Vivadent).

Figure 3 presents degree of conversion of BFRCs polymerized for 20 seconds, independently of LCU type and irradiance. Most studies reported acceptable values (≥50%) for all materials, independently of their viscosity. As observed in both scattered plots, most articles reporting acceptable depth of cure employed LCU displaying irradiance ≥1000 mW/cm^2.

Figure 4 shows the number of studies that reported acceptable hardness and degree of conversion of BFRCs polymerized for 20 seconds (classified according to LCU used) as well as studies reporting deficient polymerization. Overall, most studies showed that BFRCs (including Tetric EvoCeram/Tetric N-Ceram BFRC that contains alternative photoinitiator) can be satisfactorily polymerized using monowave or polywave LCUs. There is limited evidence assessing hardness of Beautifil Bulk restorative (Shofu Dental Corporation) and Beautifil Bulk flow (Shofu Dental Corporation) but it shows non-acceptable bottom/top hardness when cured for 20 seconds (independently of LCU). There was greater number of studies reporting satisfactory depth of cure of Surefil SDR Flow (Dentsply) and Filtek Bulk Fill flowable (3M/ESPE) restorative when polywave LCUs were used for 20 seconds.

4 | DISCUSSION

Overall, the results from our systematic review revealed that polymerization of BFRCs (at 4 mm depth) depends on material composition and radiant exposure (irradiance vs. time). In total, 33 studies were included and most of them reported material-dependent results or acceptable depth of cure for all tested BFRCs. Only two included reports presented deficient polymerization for all investigated materials.[11,16] When analyzing light curing conditions on both studies, composite resin samples were exposed for 20 seconds, similar to most included investigations.[14,15,31,33,34,44,45] Nevertheless, in both studies, delivered irradiance was reported between 700 and 800 mW/cm^2 which leads to a total energy dose of 16 J/cm^2. That may be sufficient to polymerize a 2 mm increment of conventional composite resin[19,55] but it seems to be not enough for BFRCs. In this systematic review, a secondary synthesis was also conducted using depth of cure data of BFRCs cured for 20 seconds because it is the most recommended exposure time by manufacturers. Most studies using this exposure time revealed acceptable bottom/top hardness ratio (Figure 2) and degree of conversion (Figure 3) of BFRCs using LCUs displaying irradiance ≥1000 mW/cm^2. Thus, it is possible to hypothesize that an

TABLE 1 Main methodological data and results from included studies

Author	BFRC*	Light curing unit (Manufacturer)	Monowave/ polywave	Irradiance (mW/cm^2)	Exposure time (s)	Methodology**	Results
Alrahlah et al., 2014	TEC, SF/VB, XB, FF	Elipar S10 (3M ESPE)	Monowave	1200	20	VH	Acceptable
El-Damanhoury and Platt, 2013	TEC, XF/SDR, VB	Demetron A.1 (Kerr/Sybron)	Monowave	1000 ± 50	20	KH	Material-dependent
Garcia et al., 2014	SF/VB, SDR	SmartLite iQ2 (DENTSPLY Caulk)	Monowave	800	20	KH	Non-acceptable
Ilie and Stark, 2014	TEC, XF, SF	VALO (Ultradent)	Polywave	1176	5, 20, 40	VH	Acceptable
Ilie and Stark, 2015	XB, VB, FF, SDR	VALO (Ultradent)	Polywave	1176	5, 20, 40	VH	Acceptable
Jang et al., 2015	TNCø/SDR, VB	Bluephase (Ivoclar Vivadent)	Polywave	700	40	VH	Material-dependent
Kim et al., 2015	TNCø, SF/VB, SDR	Bluephase (Ivoclar Vivadent)	Polywave	1200	20	VH	Material-dependent
Nagi et al., 2015	TEC, XF	Elipar S10 (3M ESPE)	Monowave	≥800	10, 20, 40, and 60	VH	Acceptable
ALShaafi et al., 2016	TEC, SF, XF/SDR	Bluephase 20i (Ivoclar Vivadent)	Polywave	1200	20	KH	Material-dependent
Kelic et al., 2016	TEC, XF, QF, XB/VB, SDR	Bluephase G2 (Ivoclar Vivadent)	Polywave	1120	20	VH	Acceptable
Son et al., 2016	SF, TNCø/FF, SDR, VB	L.E.Demetron (Kerr)	Monowave	900	40	VH	Material-dependent
Yap et al., 2016	BR, EP, TNCø/BF, SDR	BlueShot LED (Shofu)	Monowave	700	20	KH	Non-acceptable
Jung and Park, 2017	TNCø, SF/SDR, VB	Bluephase N (Ivoclar Vivadent)	Polywave	1140	30	VH	Material-dependent
Moharam et al., 2017	XF/SF	Elipar S10 (3M ESPE)	Monowave	1000	20	VH	Acceptable
Finan et al., 2013	XB, SDR	Optilux 501 (Kerr)	Monowave	650 ± 26	20	DC and VH	Material-dependent
Czasch and Ilie, 2013	SDR, VB	Elipar Freelight 2 (3M ESPE)	Monowave	1226	10, 20 and 40	DC and VH	Acceptable
Fronza et al., 2015	TEC, EP/SDR, FF	VALO (Ultradent)	Polywave	995 ± 2	20	DC and KH	Acceptable
Tarle et al., 2015	TEC, XF, QF, SF	Bluephase G2 (IvoclarVivadent)	Polywave	1170	10, 20 and 30	DC and KH	DC: Acceptable/KH: Material-dependent
Zorzin et al., 2015	TEC/FF, SDR, VB, XB	Bluephase 20i (Ivoclar Vivadent)	Polywave	1200	10, 20 and 30	DC and KH	Acceptable
Garoushi et al., 2016	XF, TEC, SF, EP/VB, SDR, FF	Elipar FreeLight 2 (3M ESPE)	Monowave	1000	40	DC and VH	Material-dependent
Miletic et al., 2017	TEC, SF, EP/SDR, FF	Bluephase 20i (Ivoclar Vivadent)	Polywave	1100	10 and 20	DC and VH	DC: Material-dependent/VH: Acceptable
Goracci et al., 2014	SF, EP/SDR	Demi (Kerr)	Monowave	1100	20	DC	Material-dependent
Marovic et al., 2015	XB, SDR, VB	Bluephase G2 (IvoclarVivadent)	Polywave	1170	20	DC	Acceptable
Al-Ahdal et al., 2015	EP, TEC, SF, BR/FF, VB, BF, XB	Elipar S10 (3M ESPE)	Monowave	1200	20	DC	Material-dependent
Li et al., 2015	EP, TEC/FF, SDR	Bluephase 20i (Ivoclar Vivadent)	Polywave	1174	20	DC	Acceptable
Moharam et al., 2015	TEC, XF	Elipar S10 (3M ESPE)	Monowave	≥1000	10 , 20, 40 and 60	DC	Acceptable
Papadogiannis et al., 2015	EP, SF, TEC, XF/SDR, VB, XB	Bluephase G2 (IvoclarVivadent)	Polywave	1200	30	DC	Material-dependent
Par et al., 2015	TEC, QF, XF/SDR, VB, FF, XB	Bluephase G2 (IvoclarVivadent)	Polywave	1090	20	DC	Acceptable
Pongprueksa et al., 2015	FF	Bluephase 20i (Ivoclar Vivadent)	Polywave	1100	20	DC	Acceptable

(*Continues*)

TABLE 1 (Continued)

Author	BFRC*	Light curing unit (Manufacturer)	Monowave/ polywave	Irradiance (mW/cm^2)	Exposure time (s)	Methodology**	Results
Lempel et al., 2016	XB/FF, SDR	LED C (Woodpecker)	Monowave	1100	10 and 20	DC	Material-dependent
Monterubbianesi et al., 2016	FU, FP, SF/SDR	Elipar S10 (3M ESPE) and Demi Ultra (Kerr)	Monowave	ES: 1200 and DU: 1330	20	DC	Acceptable
Par et al., 2016	TEF, SDR	Bluephase G2 (Ivoclar Vivadent)	Polywave	1185	20	DC	Acceptable
Yu et al., 2017	BR, TNCø/BF, SDR	Bluephase(Ivoclar Vivadent)	Polywave	950	20	DC	Material-dependent

*__High viscosity BFRCs__: Beautifil Bulk restorative, (Shofu Dental Corporation)-(BR); EverX posterior, (GC Europe)-(EP); Fill up, (Coltène Whaledent AG)-(FU); Filtek Bulk Fill posterior, (3M/ESPE)-(FP); Quixfil, (Dentsply)-(QF); Sonic^{TM} fill, (Kerr Corporation)-(SF); Tetric EvoCeram Bulk Fill, (Ivoclar vivadent)-(TEC); Tetric N-Ceram Bulk Fill, (Ivoclar vivadent)-(TNC) ø This bulk-fill resin composite is also marketed as Tetric EvoCeram Bulk Fill; x-tra base, (VOCO)-(XB); x-tra fill,(VOCO GmbH)-(XF); **Flowable BFRCs**: Beautifil Bulk flow, (Shofu Dental Corporation)-(BF); Filtek Bulk Fill flowable restorative, (3M/ESPE)-(FF); Surefil SDR flow, (Dentsply)-(SDR); Venus Bulk Fill, (Heraeus Kulzer)-(VB); Tetric EvoFlow Bulk Fill, (Ivoclar vivadent)-(TEF).

**VH, Vickers Hardness; KH, Knoop Hardness; DC, Degree of conversion.

TABLE 2 Risk of bias assessment of included studies

Author	Randomization	Sample size calculation	Comparable groups	Detailed information regarding measurements	Proper statistical analysis	Manufacturer's instructions	Single operator	Operator blinded	Risk of bias
Alrahlah et al.[51]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
El-Damanhoury and Platt[36]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Garcia et al.[16]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Ilie and Stark[21]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Ilie and Stark[23]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Jang et al.[37]	No	No	Yes	Yes	Yes	No	No	No	High
Kim et al.[38]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Nagi et al.[32]	No	No	Yes	Yes	No	No	No	No	High
ALShaafi et al.[39]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Kelic et al.[14]	No	No	Yes	No	No	Yes	No	No	High
Son et al.[40]	No	No	Yes	Yes	No	Yes	No	No	High
Yap et al.[11]	No	No	Yes	Yes	Yes	No	No	No	High
Jung and Park[41]	No	No	Yes	Yes	Yes	No	No	No	High
Moharam et al.[33]	No	No	Yes	Yes	Yes	No	No	No	High
Finan et al.[42]	No	No	Yes	Yes	Yes	No	No	No	High
Czasch and Ilie[20]	No	No	Yes	Yes	Yes	No	No	No	High
Fronza et al.[34]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Tarle et al.[22]	No	No	Yes	Yes	Yes	No	No	No	High
Zorzin et al.[10]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Garoushi et al.[43]	No	No	Yes	Yes	Yes	No	No	No	High
Miletic et al.[35]	No	No	Yes	Yes	Yes	No	No	No	High
Goracci et al.[50]	No	No	Yes	Yes	Yes	No	No	No	High
Marovic et al.[44]	No	No	Yes	Yes	Yes	No	No	No	High
Al-Ahdal et al.[51]	No	No	Yes	Yes	Yes	No	No	No	High
Li et al.[45]	No	No	Yes	Yes	Yes	No	No	No	High
Moharam et al.[46]	No	No	Yes	Yes	Yes	No	No	No	High
Papadogiannis et al.[52]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Par et al.[47]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Pongprueksa et al.[48]	No	No	Yes	Yes	Yes	No	No	No	High
Lempel et al.[53]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Monterubbianesi et al.[49]	No	No	Yes	Yes	Yes	Yes	No	No	Medium
Par et al.[15]	No	No	Yes	Yes	Yes	No	No	No	High
Yu et al.[54]	No	No	Yes	Yes	Yes	No	No	No	High

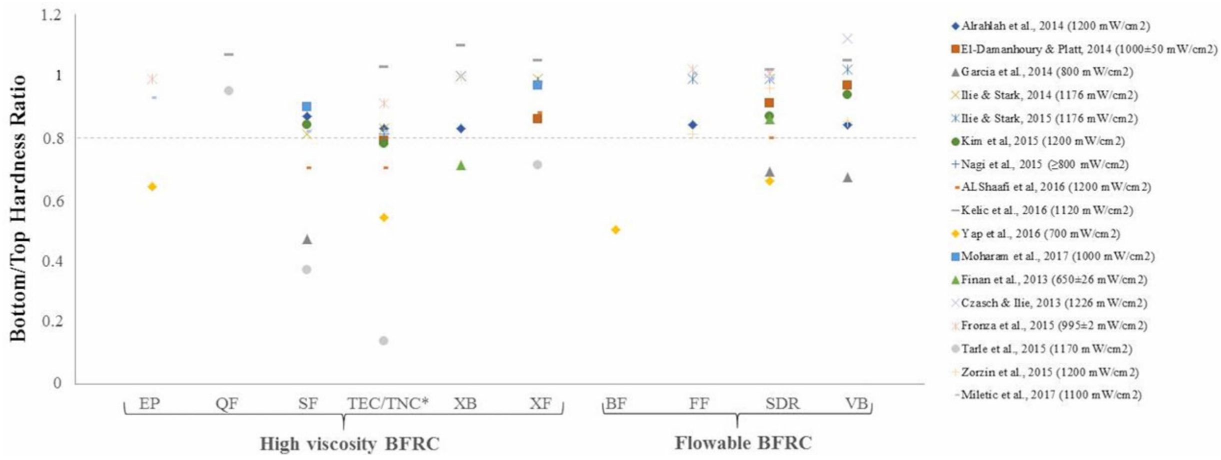

FIGURE 2 Bottom/top hardness ratio of BFRCs polymerized for 20 seconds (independently of LCU type and irradiance). **High viscosity BFRCs**: EverX posterior, (GC Europe)-(EP); Quixfil, (Dentsply)-(QF); SonicFill, (Kerr Corporation)-(SF); Tetric N-Ceram Bulk Fill, (Ivoclar vivadent)-(TNC) and Tetric EvoCeram Bulk Fill, (Ivoclar vivadent)-(TEC) are the same product, just named differently depending on which market they are sold; x-tra base, (VOCO)-(XB); x-tra fill, (VOCO GmbH)-(XF); **Flowable BFRCs**: Beautifil Bulk flow, (Shofu Dental Corporation)-(BF); Filtek Bulk Fill flowable restorative, (3M/ESPE)-(FF); Surefil SDR flow, (Dentsply)-(SDR); Venus Bulk Fill, (Heraeus Kulzer)-(VB). *BFRC containing camforoquinone and alternative photoinitiator

amount of ≥20 J/cm^2 may be the minimum energy dose required to polymerize 4 mm increments of BFRCs. Nevertheless, irradiance seems to have greater influence on the total energy dose, since extending curing times associated to lower irradiance delivery (<1000 mW/cm^2) produced deficient polymerization on some BFRCs.[37,40,43]

Besides light curing conditions, chemical related factors also play an important role on polymerization success of composite resin. Generally, filler size from some commercially available BFRCs was increased up to 20 μm which decreases total particle volume percentage. Consequently, there is a reduction in filler–matrix interface and light scattering, allowing light penetration through deeper zones.[4] In addition, material viscosity seems to be an important factor on curing success of BFRCs because many selected investigations reported higher depth of cure for flowable materials compared with some high-viscosity BFRCs.[35–43,47,49–51,53,54] In the case of flowable BFRCs, the composition percentage of inorganic filler, ranges between 64 and 75 wt%/38 and 61 vol%. Conversely, in most of high-viscosity BFRCs this component was increased up to 79–86 wt%/61–81 vol%. Therefore, flowable materials would present greater amount of organic matrix, which is mainly constituted by low-molecular weight monomers such as triethylene glycoldimethacrylate (TEGDMA) and urethane dimethacrylate (UDMA). This modification from typical resin composites composition may produce a reduction on flowable resin composites light refractive index, when compared with high viscosity materials.[56] It is noteworthy that low molecular weight monomers have higher flexibility and reactivity, which permits increased

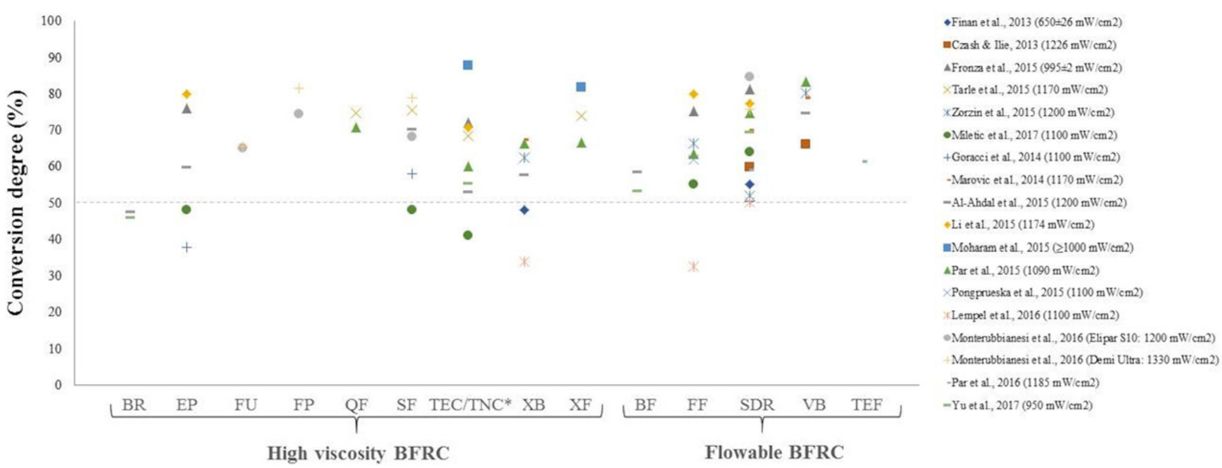

FIGURE 3 Degree of conversion of BFRCs polymerized for 20 seconds (independently of LCU type and irradiance). **High viscosity BFRCs**: Beautifil Bulk restorative, (Shofu Dental Corporation)-(BR); EverX posterior, (GC Europe)-(EP); Fill up, (Coltène Whaledent AG)-(FU); Filtek Bulk Fill posterior, (3M/ESPE)-(FP); Quixfil, (Dentsply)-(QF); SonicFill, (Kerr Corporation)-(SF); Tetric N-Ceram Bulk Fill, (Ivoclar vivadent)-(TNC) and Tetric EvoCeram Bulk Fill, (Ivoclar vivadent)-(TEC) are the same product, just named differently depending on which market they are sold; x-tra base, (VOCO)-(XB); x-tra fill,(VOCO GmbH)-(XF); **Flowable BFRCs**: Beautifil Bulk flow, (Shofu Dental Corporation)-(BF); Filtek Bulk Fill flowable restorative, (3M/ESPE)-(FF); Surefil SDR flow, (Dentsply)-(SDR); Venus Bulk Fill, (Heraeus Kulzer)-(VB); Tetric EvoFlow Bulk Fill, (Ivoclar vivadent)-(TEF). *BFRC containing camforoquinone and alternative photoinitiator

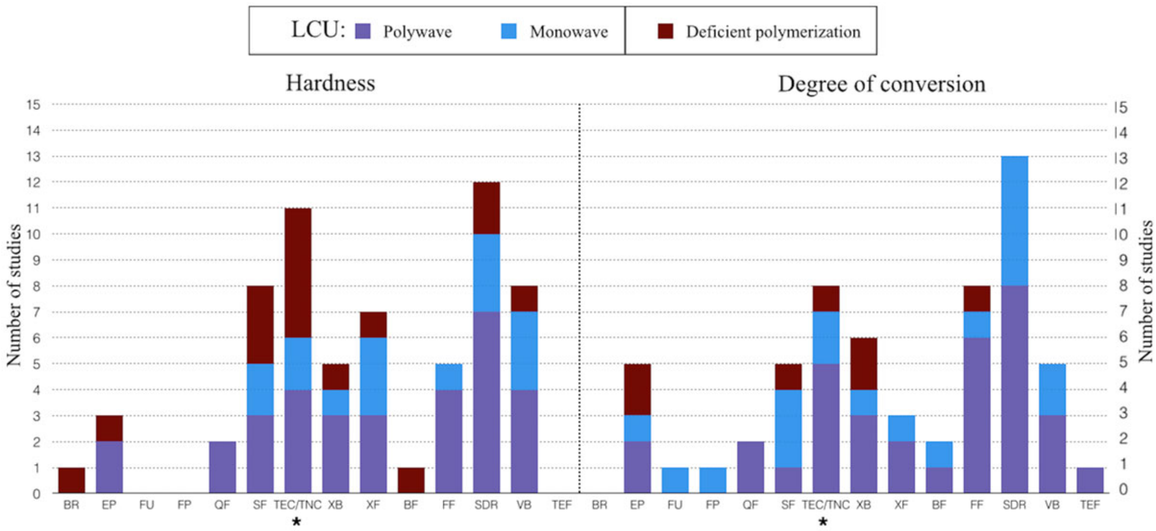

FIGURE 4 Number of studies that reported acceptable hardness and degree of conversion of BFRCs polymerized for 20 seconds (classified according to LCU used) as well as studies reporting deficient polymerization. **High viscosity BFRCs**: Beautifil Bulk restorative, (Shofu Dental Corporation)-(BR); EverX posterior, (GC Europe)-(EP); Fill up, (Coltène Whaledent AG)-(FU); Filtek Bulk Fill posterior, (3M/ESPE)-(FP); Quixfil, (DENTSPLY)-(QF); SonicFill, (Kerr Corporation)-(SF); Tetric N-Ceram Bulk Fill (Ivoclar vivadent)-(TNC) and Tetric EvoCeram Bulk Fill, (Ivoclar vivadent)-(TEC) are the same product, just named differently depending on which market they are sold; x-tra base, (VOCO)-(XB); x-tra fill,(VOCO GmbH)-(XF); **Flowable BFRCs**: Beautifil Bulk flow, (Shofu Dental Corporation)-(BF); Filtek Bulk Fill flowable restorative, (3M/ESPE)-(FF); Surefil SDR flow, (DENTSPLY)-(SDR); Venus Bulk Fill, (Heraeus Kulzer)-(VB); Tetric EvoFlow Bulk Fill, (Ivoclar vivadent)-(TEF). *BFRC containing camforoquinone and alternative photoinitiator

formation of binding sites during light curing, consequently, raising its degree of conversion.[57]

The addition of photoinitiators into the formulation of resin composites is another relevant aspect involved on materials' depth of cure performance.[58] Besides camforoquinone (CQ), an alternative photoinitiator based on Benzoyl germanium, commercially known as Ivocerin® has been incorporated into Tetric EvoCeram/Tetric N-Ceram (Ivoclar Vivadent) Bulk Fill. This photoinitiator is classified as type I which means that it does not require a co-initiator to produce free radicals.[24,59] As a matter of fact, it presents greater reactivity during light curing, which can be considered beneficial when larger material volume is being polymerized in a single increment. Nevertheless, Benzoyl germanium photoinitiator is sensitive at lower wavelengths (between 380 and 450 nm), compared with CQ (450–490 nm) which acts as photoinitiator in most of conventional and BFRCs.[10,60] Hence, this alternative photoinitiator may not be excited by monowave LCUs as they deliver photons only within blue light spectrum (400–500 nm). For these reasons, the usage of polywave LCUs are recommended because they emit both types of wavelengths, the shorter (violet spectrum) to activate type I initiators, and longer ones (blue spectrum) for CQ.[55,61]

In some included studies, polywave LCUs, as Bluephase (Ivoclar Vivadent) and VALO (Ultradent Products) were employed to cure TetricEvoCeram Bulk Fill/Tetric N-Ceram Bulk Fill (Ivoclar Vivadent), achieving acceptable bottom/top hardness ratios (≥0.8) and degree of conversion (≥50%).[10,14,21,34,45,47] Few other studies used a monowave LCU (Elipar S10, 3M/ESPE) to polymerize the same material as well, but employing exposure times of 20 and 60 seconds, while delivering around >1000 mW/cm^2 irradiance.[31,32,46] Interestingly, the mentioned studies also reported acceptable depth of cure for such alternative photoinitiator-containing material (Figure 4). This may be explained by the fact that longer wavelengths (blue spectrum) exhibit deeper penetration into resin material compared with shorter ones (violet spectrum). Therefore, a greater influence of wavelengths width is expected on both photoinitiators (CQ and Benzoyl germanium) at the top surface of BFRC restoration.[12] Nevertheless, in deeper areas, short wavelengths are inefficient and only longer wavelengths (as blue light) would penetrate enough, consequently in this case only CQ would be excited.[12] It is noticeable that polywave LCUs usage was not an essential factor as irradiance and exposure time to properly polymerize the BFRC containing alternative photoinitiator. Therefore, it is imperative to check irradiance from LCU (monowave or polywave) through the use of radiometers.[18,55]

Nowadays, there is a growing tendency between dental professionals to use BFRCs to reduce and simplify clinical steps, facilitating restorative procedures. However, caution should be taken when performing some "clinical shortcuts" such as using high irradiance LCUs while shortening exposure times, because it may increase polymerization shrinkage stress of resin-based materials. This natural behavior of resin composites is strongly influenced by insertion technique, C-factor and material's volume delivered into the cavity.[62,63] Thereby, considering that larger increments are placed in BFRCs technique and that high irradiance LCUs are recommended, a consensus regarding real consequences on polymerization shrinkage and associated-stress on dental structure promoted by these novel restorative materials is urgently needed.

Extensive electronic searches conducted in different databases in addition to some other complementary analysis, provided a broad overview of the collected information, which may be considered as the main strength of this research. Furthermore, strict and systematic methods were applied during data extraction besides posterior risk of bias assessment, in order to properly analyze the selected works.

Nonetheless, the main limitation detected was high prevalence of medium to high risk of bias among most of the analyzed evidence, which actually may be fairly common in in-vitro studies as has already been reported in previous systematic reviews.[29,30] Finally, selected articles presented significant methodological heterogeneity, especially in terms of tested materials, irradiance from LCU, exposure times, assessment methods and obtained outcomes, which made impossible to conduct a meta-analysis.

5 | CONCLUSIONS

1. BFRCs reach acceptable depth of cure (at 4 mm) depending on material and light curing conditions.
2. LED devices displaying irradiance ≥1000 mW/cm^2 (monowave/ polywave) and exposure times around 20 seconds are mainly recommended to achieve acceptable depth of cure in most of BFRCs (at 4 mm).
3. The use of polywave light curing units was useful but not strictly necessary for BFRC containing an alternative photoinitiator.

DISCLOSURE

The author does not have any financial interest in any of the companies whose products are included in this article.

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