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Laboratory Research

Effect of Shortened Light-Curing Modes on Bulk-Fill Resin Composites

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Clinical Relevance

Shortened light curing does not affect volumetric polymerization shrinkage or cohesive tensile strength but negatively affects the shear bond strength of some bulk-fill resin composites. When performing shortened light curing, clinicians should be aware of the light output of their light-curing units.

SUMMARY

Purpose: To evaluate volumetric polymerization shrinkage (VPS), shear bond strength (SBS) to dentin, and cohesive tensile strength (CTS) of bulk-fill resin composites (BFRCs) light activated by different modes.

Methods and Materials: Six groups were evaluated: Tetric EvoCeram bulk fill + high mode (10 seconds; TEC H10), Tetric EvoFlow bulk fill + high mode (TEF H10), experimental bulk fill + high mode (TEE H10), Tetric EvoCeram bulk fill + turbo mode (five seconds; TEC T5), Tetric EvoFlow bulk fill + turbo mode (TEF T5), and experimental bulk fill + turbo mode (TEE T5). Bluephase Style 20i and Adhese Universal Vivapen were used for all groups. All BFRC samples were built up on human molar bur-prepared occlusal cavities. VPS% and location were evaluated through micro–computed tomography. SBS and CTS tests were performed 24 hours after storage or after 5000 thermal cycles; fracture mode was analyzed for SBS.

Results: Both TEC H10 and TEE H10 presented lower VPS% than TEF H10. However, no significant differences were observed with the turbo-curing mode. No differences were observed for the same BFRC within curing modes. Occlusal shrinkage was mostly observed. Regarding SBS, thermal cycling (TC) affected all groups. Without TC, all groups showed higher SBS values for high mode than

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turbo mode, while with TC, only TEC showed decreased SBS from high mode to turbo modes; modes of fracture were predominantly adhesive. For CTS, TC affected all groups except TEE H10. In general, no differences were observed between groups when comparing the curing modes.

Conclusions: Increased light output with a shortened curing time did not jeopardize the VPS and SBS properties of the BFRCs, although a decreased SBS was observed in some groups. TEE generally showed similar or improved values for the tested properties in a shortened light-curing time. The VPS was mostly affected by the materials tested, whereas the SBS was affected by the materials, curing modes, and TC. The CTS was not affected by the curing modes.

INTRODUCTION

In current practice, there is hardly a dental procedure that does not require the use of a polymeric resin material and light activation.[1] Resin composite restorations present good esthetic and mechanical properties as well as adhesion to the tooth structure using an adhesive system; however, the time spent on performing these procedures is a drawback.[2] For that reason, and as a matter of improving clinical efficiency, bulk-fill resin composites (BFRCs) were introduced in the market, and numerous *in vitro* studies have evaluated these restorative materials.[3-17] BFRCs present modifications in their compositions, such as new monomers and changes in their concentrations, addition of new photoinitiators, increased translucency, and decreased or changes in their inorganic content. All of these modifications have allowed them to be applied in a 4- to 5-mm thicknesses, thus diminishing the time spent on the restorative procedure.[16] Moreover, they are presented in two different formulations with high and low viscosity; the latter requires a capping layer of regular resin composite for finishing the restoration because of its weak mechanical properties,[5,12] which compromises the time-saving benefit by adding an extra step.[10]

Most of the published literature suggests that BFRCs have good performance in terms of degree of conversion,[13,14] polymerization shrinkage,[3,15] and bonding properties.[8] Although BFRCs are a faster procedure compared with the incremental technique, clinicians still aim to save more time. Thus, there has recently been a move toward an even faster light activation of BFRCs.[18] Such time-saving procedures should not be detrimental to the material's mechanical properties, because adequate light curing is required for resin composite restorations to reach their manufacturer's intended properties and ensure predictable long-term clinical success.[1] It seems logical that if a restoration does not receive sufficient incident irradiance, mostly for a 4-mm-depth BFRC restoration, it will not reach its ideal mechanical and bonding properties to the teeth,[1] which could lead to bulk fracture of the restoration, secondary caries due to adhesive failure, and breakdown of the margin.[19,20]

The third-generation light-emitting diode (LED) light-curing units (LCUs), also called "polywave," provide a broad-spectrum LCU that can activate all current photoinitiators present in resin composites.[18] The need for such LCUs is because different photoinitiators, apart from the conventional camphorquinone (light activated within the blue range, about 460-470 nm), are being used in formulations of resin composites. These are type I photoinitiators, and need another range of delivered light.[18] Such photoinitiators (eg, Lucirin TPO and derivatives of dibenzoyl germanium such as Ivocerin) do not need additional co-initiators, as they decompose directly into 1 or more free radicals when sufficient energy at the correct wavelength is delivered.[18]

Ivocerin is most reactive at 408 nm but remains very sensitive to wavelengths of light between 400 and 430 nm. It is considered an "initiation booster" because of its ability to start the reaction with fewer photons, polymerize deeply, and regulate polymerization during curing of a material in bulk.[21] Also, the greater ability of these materials to create free radicals per molecule unit can improve the light sensitivity of resin composites.[22] Thus, depending on the photoinitiators used, even small changes in the emission spectrum (wavelength) can be relevant.[18] Apart from the wavelength needed, the irradiance is also an important factor when light curing a resin composite.[18] The introduction of LED LCUs with high power and short exposure has raised concerns regarding effectiveness, to ensure that the restoration is not undercured.[7,22,23]

One of the most investigated properties of BFRCs is polymerization shrinkage,[3,4,15] an unavoidable phenomenon that occurs because of the polymerization reaction of all resinous materials when the monomers are converted to polymers. Its undesirable clinical outcomes include shrinkage stress on the tooth-restoration interface, which can form gaps at the interface, and marginal infiltration.[3,15] Volumetric polymerization shrinkage (VPS) can be observed

Table 1: *Detailed Information of the Bulk-Fill Resin Composites Used in This Study*

Material	Type, Shade	Manufacturer, Batch	Composition
Tetric Evoceram bulk fill	High-viscosity bulk-fill resin composite, IVA	Ivoclar Vivadent, W02598	Bis-GMA, UDMA, ytterbium trifluoride, dimethacrylate, barium glass, mixed oxide, prepolymer, additives, catalyst stabilizers 0.9 wt.%; pigments <0.1 wt.%; 79-81 wt% inorganic fillers. Photoinitiator present: Ivocerin
Tetric Evoflow bulk fill	Low-viscosity bulk-fill \resin composite, IVA	Ivoclar Vivadent, V41879	Bis-GMA, urethane dimethacrylate, decandiol dimethacrylate, 37.6 wt.% barium glass filler, ytterbium trifluoride, mixed oxide, highly dispersed silicon dioxide 41.1 wt.%, prepolymer 20.4 wt.%, additives, catalyst stabilizers 0.9 wt.%, pigments <0.1 wt.%; 62 wt.% inorganic fillers; photoinitiator present: Ivocerin
F-Composite 2 (experimental)	Experimental, IVA	Ivoclar Vivadent, W06912	Composition similar to its high-viscosity bulk-fill composite counterpart (Tetric Evoceram bulk fill), with a modification of double the amount of the Ivocerin

Abbreviations: Bis-GMA, bisphenol A diglycidyl ether dimethacrylate; UDMA, urethane dimethacrylate.

through a nondestructive, three-dimensional, high-resolution imaging technique test called micro–computed tomography (μCT),[3,4,15] which has been used for different purposes, such as evaluating cementation film thickness,[24] presence of bubbles with different cementation techniques,[25] and polymerization shrinkage vectors.[26]

Mechanical properties[5,6,12] play a fundamental role in the clinical performance of a restorative material. It can be evaluated through a great number of tests, such as degree of conversion, hardness, and tensile tests.[8,14,27] As stated in a recent study, it is likely that most dental restorations fail by tensile stresses set up within their structure because of the loading mechanism of their complex geometries.[27]

The bonding to the tooth structure is also an important parameter that needs attention when dealing with BFRCs, as the light beam from the LCU decreases with distance.[8] Thus, the interface between the resin composite and tooth, which is where the adhesive system is located, is a critical spot, as it is the one farther away from the LCU's light tip. A reduction in the bond strength to dentin at the bottom of the cavity in class I restorations with BFRCs has been shown in the literature.[17]

Aiming to mimic the degradation of the oral environment, TC is an effective *in vitro* aging protocol, performed to create thermal strains at the bonding interface caused by thermal changes in water baths. Moreover, repetition of such baths were shown to weaken the bond between the resin matrix and filling material.[28]

Thus, the aim of the present study is to determine the influence of different light-curing modes (high mode and turbo mode) of a single LCU on the VPS, shear bond strength (SBS) to dentin, and cohesive tensile strength (CTS) of two commercial and one experimental BFRC. The hypotheses tested were the following: 1) different light-curing modes would affect the VPS, SBS, and CTS of different BFRCs, and 2) within a given BFRC, there would be significant differences regarding VPS, SBS, and CTS light activated with different curing modes.

METHODS AND MATERIALS

Material composition, manufacturers, and batch numbers are described in Table 1. Three different BFRCs were used: Tetric EvoCeram bulk fill (TEC; Ivoclar Vivadent, Schaan, Liechtenstein), Tetric EvoFlow bulk fill (TEF; Ivoclar Vivadent), and an experimental BFRC containing double the Ivocerin photoinitiator than its counterpart TEC (Tetric EvoCeram Experimental bulk fill [TEE]; Ivoclar Vivadent). All materials were light activated by the same LCU (Bluephase Style 20i, Ivoclar Vivadent) at two different curing modes: high mode for 10 seconds (H10; approximately 1200 mW/cm^2) and turbo mode for five seconds (T5; approximately 2000 mW/cm^2). Power outputs of the LCU were checked with a Bluephase Meter II (Ivoclar Vivadent) before and after all tests. All teeth used in the present study were obtained according to protocols approved by the New York University Ethical Committee.

Assessment of VPS and the Location

Thirty-six caries-free human third molars had their cusps flattened, and standardized boxed-shaped class I preparations (4-mm depth × 4-mm length × 4-mm width) were made with a diamond bur (AD20

Occlusal reduction bur, code 845-022; Strauss, Westport, CT, USA), which was replaced every five cavity preparations. Final cavity dimensions were checked with a digital caliper, and teeth were maintained in distilled water (25°C) until their use. Teeth were randomly divided into six groups (n=6 per group) according to BFRC and light-curing mode used: G1, TEC H10; G2, TEF H10; G3, TEE H10; G4, TEC T5; G5, TEF T5; and G6, TEE T5. All groups were light activated by the same LCU (Bluephase Style 20i) and used the same adhesive system (Adhese Universal Vivapen, Ivoclar Vivadent), which was light activated according to the same designated time as for the BFRCs. The adhesive system was used in a self-etching procedure, after cleaning the cavities with a pumice slurry. All cavities were filled in the bulk technique.

Each tooth was scanned three times using a μCT apparatus (μCT40, Scanco Medical, AG, Basserdorf, Switzerland), calibrated using a phantom standard at 70 kVp/BH 200 mgHA/cm. The operating condition for the μCT device used was 70 kVp to 114 microamperes with a resolution of 16 μm/slice. The average of the total number of slices was approximately 250, and the average scan time was 28 minutes, as previously described.[3,15]

The first scan was performed after cavity preparation. This procedure was required for avoiding scattering and possible noise between the restorative material and the tooth structure but also to minimize possible artifacts in the threshold segmentation, because enamel, dentin, and restorative material present similar radiodensity.[3,4,15] The second scan was performed after application of the adhesive system and resin composite and before the light-curing procedure (uncured scan); the third scan was done after light curing the samples (cured scan). During the scans, all samples were kept in a dark vial to prevent any contact with a light source for unwanted polymerization.

Acquired μCT data were imported into a workstation and evaluated with Amira software (version 5.5.2, VSG, Burlington, MA, USA). All scans were superimposed with the Amira software tool called "superimposition," providing a perfect arrangement of all images. Registered μCT data of uncured and cured samples were subtracted from the cavity data, isolating the restoration (uncured scan minus cavity preparation scan, and cured scan minus cavity preparation scan). This procedure enabled both uncured and cured resin composite volumes to be isolated and quantified, allowing the total VPS to be calculated as a percentage. Shrinkage observed on the top and bottom/sides of the cavity were also evaluated; for that purpose, separation within the top and bottom/sides locations was evaluated with the Amira tool called "extract surface" and measured separately, also calculated as percentages. Location data were presented regarding the top surface, and the rest of the shrinkage was considered as bottom/sides.

Data regarding total VPS measurement and VPS in the different locations from the cavity (top and bottom/sides) were analyzed by a normality test followed by a two-way analysis of variance (ANOVA) and least significant difference (LSD) post hoc tests using 95% confidence intervals.

Assessment of SBS With and Without Thermal Cycling

One hundred twenty caries-free human third molars had their roots removed and crowns sectioned with a low-speed diamond disk saw under water cooling to expose mid-coronal dentin. Exposed surfaces were abraded in a semiautomatic polishing machine (LaboPol-6, Struers, Madrid, Spain) with 500-grit silicon carbide abrasive paper under water cooling, in order to standardize the smear layer. Groups were divided as previously described: G1, TEC H10; G2, TEF H10; G3, TEE H10; G4, TEC T5; G5, TEF T5; and G6, TEE T5. All groups were light activated by the same LCU (Bluephase Style 20i) and the same adhesive system (Adhese Universal Vivapen, Ivoclar Vivadent), which was light activated according to the same designated time as for the resin BFRCs. The adhesive system was used in a self-etching procedure, after cleaning the cavities with a pumice slurry.

The BFRC was built up in bulk through a disc with a central orifice (Ø=3.0 mm and 4-mm high), which was centered on the occlusal tooth surface to obtain the standardized resin composite bar for the SBS test. All resin blocks were prepared in a single increment.

After the restorative procedures, samples were subdivided in two subgroups (n=10): 1) storage in distilled water at 37°C for 24 hours or 2) 5000 thermal cycles in water baths for 30 seconds in each bath of 5°C and 55°C in a thermal cycling (TC) simulator machine.

After the designated storage period, each sample was placed in an SBS testing machine (Shear Bond Tester, Bisco Dental, Schaumburg, IL, USA), and SBS was measured at a cross-head speed of 1 mm/min. The maximum load of SBS of the composite

Table 2: *Volumetric Polymerization Shrinkage (VPS) of Three Bulk-Fill Resin Composites Tested Under High- and Turbo-Curing Modes*[a]

Material	Curing Mode	
	High, 10 s	Turbo, 5 s
Volumetric polymerization shrinkage		
Tetric EvoCeram bulk fill (TEC)	2.6 (0.3) Ab	2.4 (0.2) Aa
Tetric EvoFlow bulk fill (TEF)	3.0 (0.4) Aa	2.8 (0.6) Aa
Experimental bulk fill (TEE)	2.7 (0.4) Ab	2.3 (0.4) Aa
Top shrinkage		
Tetric EvoCeram bulk fill (TEC)	88.8 (8.9) Aab	97.2 (7.4) Aa
Tetric EvoFlow bulk fill (TEF)	97.7 (9.2) Aa	98.7 (15.7) Aa
Experimental bulk fill (TEE)	80.5 (10.4) Ab	80.1 (9.2) Ab

[a] *Data represent the mean (SD) of the total VPS% and the shrinkage percentage located on the top (unbonded surface). Location data were presented regarding the top surface, as the rest of the shrinkage was considered as bottom/sides (bonded surfaces) shrinkage. Here, the letters (A, a, b) indicate statistical comparisons of different composites and curing modes (p<0.05). Uppercase letters compare different curing modes within the same composite (in the horizontal direction), whereas the lowercase letters compare different composites within the same curing modes (in the vertical direction).*

resin to dentin was recorded in newtons (N) and calculated in MPa, taking into account the cross-sectional area of the composite buildup. The SBS data were analyzed by normality test, followed by a three-way ANOVA and LSD post hoc tests using 95% confidence intervals.

After SBS testing, the fracture mode of each specimen was determined under a loupe (Panoramic Flip-up Adivista 2.5x; PeriOptix Inc, Lompoc, CA, USA) at 2.5× magnification and classified as 1 = adhesive fracture, 2 = cohesive fracture in dentin, 3 = cohesive fracture in resin composite, 4 = mixed fracture (adhesive + dentin), or 5 = mixed fracture (adhesive + resin composite).

Assessment of CTS With and Without TC

One hundred twenty beam-shaped samples with a cross-sectional area of approximately 1 mm^2 were constructed with a silicon matrix. Groups were divided as previously described for the SBS test: G1, TEC H10; G2, TEF H10; G3, TEE H10; G4, TEC T5; G5, TEF T5; and G6, TEE T5. After that, samples were subdivided into two subgroups (n=10): 1) storage in distilled water at 37°C for 24 hours or 2) 5000 thermal cycles in water baths for 30 seconds in each bath of 5°C and 55°C in a TC simulator machine.

After the designated storage period, each beam was individually fixed to a microtensile device with a cyanoacrylate-based glue (Zapit, Dental Ventures of America, Corona, CA, USA) and attached to a universal testing machine (Micro Tensile Tester, Bisco Dental). Specimens were tensile loaded until fracture at a cross-head speed of 1 mm/min. The CTS values were recorded in MPa. Data were analyzed by a normality test, followed by a three-way ANOVA and LSD post hoc tests using 95% confidence intervals.

RESULTS

Table 2 shows the VPS for the different BFRCs and curing modes and also the main location where it occurred. Only the top surface results are described in Table 2, as the rest of the shrinkage was considered as bottom/sides. Figure 1 shows the representative images obtained by the μCT scans. No significant differences in VPS were observed between the high and turbo curing modes for any BFRC ($p>0.05$). For turbo mode, no statistical differences were observed between the different BFRCs ($p>0.05$), except for the high curing mode, in which TEF showed statistically higher VPS% than both TEC ($p=0.032$) and TEE ($p=0.036$). For all BFRCs and curing modes, most of the VPS occurred at the top, the unbonded portion, of the restoration ($p<0.05$). Regarding the different curing modes within the same material, no statistical differences were observed in shrinkage location within the curing modes for any BFRC ($p>0.05$). However, when the same curing mode was evaluated comparing different BFRCs, for turbo mode, TEE showed statistically less VPS% on top of the restoration than TEC ($p=0.001$) and TEF ($p=0.003$). For the high-curing mode, TEF presented statistically the same VPS% on the top of the restoration of TEC ($p=0.379$) but was statistically different when compared with TEE ($p=0.026$), whereas TEC and TEE showed statistically similar VPS% on top of the restoration ($p=0.156$).

Table 3 shows the results from the SBS test for the different BFRCs at each curing mode, with and without TC. For all materials, the high-curing mode presented a higher SBS than turbo-curing mode, in which no TC was performed ($p\leq0.05$). When TC was performed, only the values of TEC decreased statistically from high- to turbo-curing mode ($p=0.018$), while for the other BFRCs, the values comparing both curing modes showed no significant

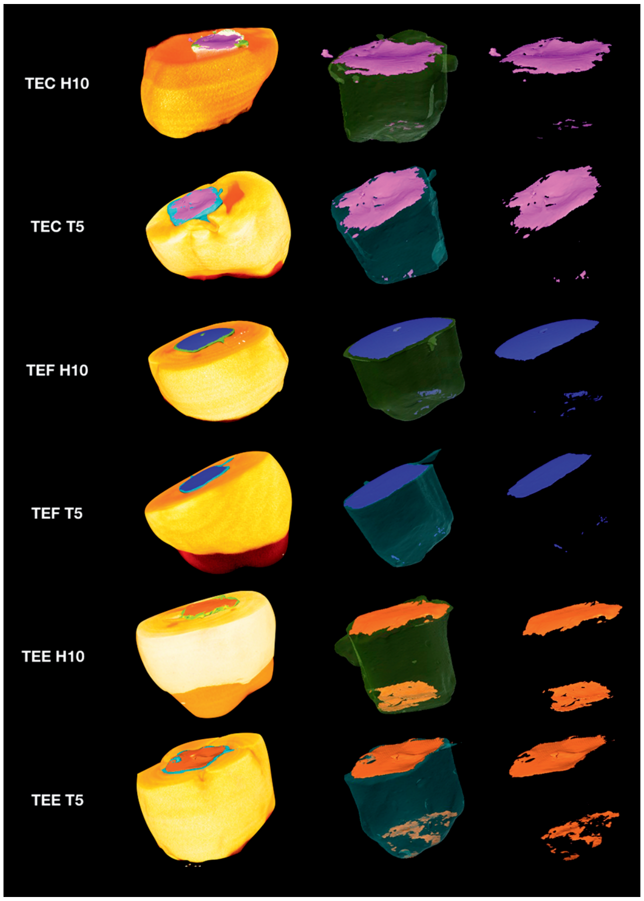

Figure 1. *Micro–computed tomography (μCT) scans of three bulk-fill resin composites tested under high (10 seconds) and turbo (five seconds) curing modes. The images show the location of shrinkage in pink (groups TEC H10 and T5), blue (groups TEF H10 and T5), and orange (groups TEE H10 and T5). Observe that the shrinkage was mostly frequent in the occlusal (unbonded surface) for all samples. Images from the left column show the restored teeth, the middle column shows the restoration and shrinkage digitally extracted from the tooth, and the right column shows the shrinkage only.*

differences ($p>0.05$). When comparing the BFRCs with and without TC at the same curing mode, all groups showed a statistically decreased SBS when TC was performed ($p\leq0.05$). When the different BFRCs were compared within the high-curing mode without TC, TEF and TEE showed a statistically similar SBS ($p=0.200$), and TEF showed an increased SBS when compared with TEC ($p=0.035$), a pattern that was repeated for turbo-curing mode without TC. When samples were subjected to TC and the different BFRCs were compared with the same curing mode, no statistical differences within the BFRCs were observed for the high-curing mode ($p>0.05$), while for the turbo-curing mode, the experimental TEE composite showed a statistically higher SBS than the other groups, TEC ($p=0.002$) and TEF ($p=0.007$), with no statistical difference between the groups ($p=0.578$).

Table 3: *Shear Bond Strength (SBS) of Three Bulk-Fill Resin Composites Tested Under High- and Turbo-Curing Modes*[a]

Material	Curing Mode	
	High, 10 s	Turbo, 5 s
Without TC		
Tetric EvoCeram bulk fill (TEC)	23.6 (3.6) Ab[b]	19.5 (4.3) Bb[b]
Tetric EvoFlow bulk fill (TEF)	27.3 (2.9) Aa[b]	23.7 (4.6) Ba[b]
Experimental bulk fill (TEE)	25.8 (6.6) Aab[b]	20.8 (3.4) Bab[b]
With TC		
Tetric EvoCeram bulk fill (TEC)	13.3 (3.4) Aa	8.3 (2.8) Bb
Tetric EvoFlow bulk fill (TEF)	12.7 (4.3) Aa	9.4 (2.6) Ab
Experimental bulk fill (TEE)	10.9 (4.6) Aa	14.7 (4.0) Aa

[a] Data represent the mean (SD) with and without thermal cycling (TC). Here, the letters (A, B, a, b) indicate statistical comparisons of different composites and curing modes (p<0.05). The uppercase letters compare different curing modes within the same composite (in the horizontal direction), whereas the lowercase letters compare different composites within the same curing modes under the same thermal cycling condition (in the vertical direction).
[b] Comparison of the same composite and curing mode with and without thermal cycling (p<0.05).

The SBS modes of fracture are presented in Table 4. This was predominantly adhesive for TEC H10s and TEC T5s, both with and without TC. Regarding TEF, without TC, for both high mode and turbo mode, the most predominant modes of fracture were adhesive and mixed (adhesive/resin). For samples subjected to TC, fractures were predominantly adhesive for both curing modes. When TEE was analyzed, the predominance of the fracture modes was adhesive for TEE H10s and TEE T5s both with and without TC.

Table 5 shows the results from the CTS test for the different BFRCs at each curing mode, with and without TC. When the same BFRC was compared in different light-curing modes, both with and without TC, no statistical differences were observed ($p>0.05$). When comparing the BFRCs with and without TC using the same curing mode, all materials showed a statistical decrease in CTS when TC was performed ($p<0.05$), except for TEE H10, for which the CTS values were statistically similar both with and without TC ($p=0.181$). When the different BFRCs were compared within the high-curing mode with or without TC, no statistical differences were observed within the BFRCs ($p>0.05$), while for the

Table 4: *Fracture Mode in the Shear Bond Strength (SBS) of Three Bulk-Fill Resin Composites Tested Under High (H10)–and Turbo (T5)—Curing Modes, With or Without Thermal Cycling (TC)*

Fracture Mode	Without TC						With TC					
	TEC H10	TEC T5	TEF H10	TEF T5	TEE H10	TEE T5	TEC H10	TEC T5	TEF H10	TEF T5	TEE H10	TEE T5
Adhesive	9	10	5	4	7	9	10	10	9	10	10	8
Cohesive in dentin	0	0	0	0	0	0	0	0	0	0	0	0
Cohesive in resin	0	0	0	0	0	0	0	0	0	0	0	0
Mixed (adhesive + dentin)	0	0	5	4	1	0	0	0	0	0	0	1
Mixed (adhesive + resin)	1	0	0	2	2	1	0	0	1	0	0	1

turbo-curing mode, TEF presented higher cohesive strength than TEE (p=0.012) when TC was not performed. However, it presented no significant difference compared with TEC (p=0.100). When TC was performed, again, no statistical differences were observed among BFRCs (p>0.05).

DISCUSSION

The first hypothesis tested was accepted, because different light-curing modes affected the VPS, SBS, and CTS of BFRCs. The second hypothesis tested was also accepted, since different BFRCs promoted significant differences regarding VPS, SBS, and CTS light activated with different curing modes.

Table 5: *Cohesive Tensile Strength (CTS) of Three Bulk-Fill Resin Composites Tested Under High- and Turbo-Curing Modes*[a]

Material	Curing Mode	
	High, 10 s	Turbo, 5 s
Without TC		
Tetric EvoCeram bulk fill (TEC)	60.7 (7.0) Aa[b]	56.43 (12.2) Aab[b]
Tetric EvoFlow bulk fill (TEF)	61.3 (12.2) Aa[b]	63.57 (7.9) Aa[b]
Experimental bulk fill (TEE)	53.7 (9.5) Aa	52.35 (6.3) Ab[b]
With TC		
Tetric EvoCeram bulk fill (TEC)	47.7 (5.5) Aa	42.91 (8.2) Aa
Tetric EvoFlow bulk fill (TEF)	52.4 (11.3) Aa	51.08 (7.1) Aa
Experimental bulk fill (TEE)	47.3 (7.8) Aa	43.12 (18.1) Aa

[a] *Data represent the mean (SD) with and without thermal cycling (TC). Here, the letters (A, a, b) indicate statistical comparisons of different composites and curing modes (p<0.05). The uppercase letters compare different curing modes within the same composite (in the horizontal direction), whereas the lowercase letters compare different composites within the same curing modes under the same thermal cycling condition (in the vertical direction).*
[b] *Comparison of thermal cycling (without vs with) in the same composite and curing mode (p<0.05).*

The VPS percentages corroborate those of other studies,[3,4,15] ranging from 2.3% to 3.0%. The low-viscosity TEF presented higher VPS than the other BFRCs tested for high-curing mode, TEC and TEE, an expected result, as TEF presents fewer inorganic fillers than its high-viscosity counterpart (62wt% and 79-81wt%, respectively). Previous reports showed that composites with lower filler content could result in higher VPS% than high-viscosity ones, because high-viscosity resin composites commonly present reduced monomer content.[29] However, no differences within the BFRCs were observed for the turbo mode, which can be explained by the faster polymerization using this light-activation mode, which could have reduced the pre-gel phase, forming short chains before the solid state is reached.[29,30] BFRCs did not show a significant difference when the different curing modes were evaluated. This result is in accordance with a recent study[4] that evaluated a single BFRC light activated with four different types of curing modes and observed no significant differences within them. However, the present study disagrees with the findings of other studies that showed that a light-curing protocol with lower irradiance and longer exposure time resulted in lower VPS, as slower polymerization forms longer chains with higher molecular weight compared with higher irradiance,[5] a phenomenon not observed in the present study.

Regarding shrinkage location, for all groups, top shrinkage was detected more often than bottom/sides shrinkage, an expected result, as a higher VPS% has been demonstrated where there is no adhesive interface (unbonded surface), for instance, the occlusal surface.[3,4,15] When the different BFRCs were compared, the experimental BFRC (TEE) showed a lower top (occlusal) VPS% than the other investigated materials and thus more VPS% in the bonded walls. This result could be related to the increased amount of photoinitiator in its composition, which could have resulted in a higher degree of polymerization in deeper regions, thus promoting more VPS in the bottom/sides than the other BFRCs.[3,15] Further studies should focus on comparing the VPS% and degree of conversion of resin composites with increased photoinitiators. Thus, according to the present study, with regard to VPS, it was observed that the parameter is mostly affected by the materials used rather than by the curing modes.

The SBS test demonstrated decreased values for all BFRCs with TC. The deterioration of the adhesive interface after thermal aging is in accordance with the literature.[31] A recent study observed the deterioration of different universal adhesives, including the one used in this study, and found lower SBS and a less stable marginal sealing capability than in the immediate condition.[32] This can be explained by the fact that TC produces hoop stress[33] as a result of the unequal thermal expansion of the different substrates compromised in the bonded interface, which could induce volumetric changes in the adhesive layers.[34] The SBS results also reflect the fracture modes observed in the present study, predominantly adhesive for all materials with TC, while without TC, TEF was the BFRC that resulted in more samples with a mixed type of fracture, which explains its higher SBS values compared with the other BFRCs. Without TC, all BFRCs tested showed a significant decrease in SBS when turbo mode was used compared with high mode. With TC, only TEC showed significantly decreased values for turbo mode compared with high mode, whereas TEF and TEE materials showed no statistical differences between high and turbo modes. This can be explained by the evidence that the flowable composite has higher translucency before polymerization, and the experimental composite, because of its increased amount of photoinitiator, could cause more stable adhesion with TC. It has been proven that the greater absorption of this photoinitiator also contributes to an increased depth of cure of resin materials.[5,21]

When comparing the SBS of the different BFRCs within the same light-curing mode, for both high and turbo modes without TC, TEF and TEE showed the highest results, while TEC and TEE were not significantly different from each other. For the results with TC, the different BFRCs did not show significant between-group differences when using high mode, although for the turbo-curing mode, the experimental material TEE showed higher SBS values than those obtained for TEC and TEF. It was observed in a previous work from this group that the violet light loses its power with increased depths.[26] With a higher amount of Ivocerin in the experimental material TEE, deep regions (eg, 4 mm) could have been more polymerized by both emitted lights (blue and violet) from the Bluephase Style 20i. The light activation of the experimental TEE with turbo mode resulted in a lack of significant differences between it and high mode. When this experimental material was evaluated with TC, higher SBS results were obtained using turbo mode compared with the other BFRCs studied.

The CTS values demonstrated no difference in light-curing mode for any of the BFRCs, both with or without TC. Although these results cannot be compared with the findings of any other study, as the CTS of BFRCs has not been investigated so far, they do agree with the VPS% results, as no differences were observed between the light-curing modes. However, significant differences were observed when TC aging was compared, as all BFRCs showed a decrease in CTS values, except for TEE H10. This result was expected, as it is known that thermal aging negatively affects the mechanical properties of resinous materials because of their expansion and shrinkage, which could weaken the bonds that connect the structure of the resin.[35] The lack of significant differences when TC was performed or not was observed only for the experimental BFRC; however, no significant differences were observed within the different materials with TC.

It has been shown that longer curing times at lower irradiances improve the mechanical properties of resin composites, and an increased volume of photoinitiator can also positively affect this parameter.[29] A significant difference among the different BFRCs was observed only for turbo mode without TC, in which the experimental BFRC TEE presented a lower CTS than the flowable BFRC did. This result was not expected, because this material has a greater amount of inorganic fillers than its flowable version. However, a possible explanation for this result is the increased translucency of the flowable material when compared with high-viscous materials before polymerization,[5] which allows more light transmission through the material, possibly improving its mechanical properties. A limitation of this result is that the CTS test was performed in a 1-mm^2 beam sample. BFRCs are intended to be cured at up to 4-mm thickness; thus, the size of the sample could be related to the lack of statistically significant differences within the BFRCs.

The use of increased emitted irradiance in a reduced time has been suggested to save time during restorative procedures. However, results from the present study suggest that the use of a reduced curing time should be done with caution, mostly regarding the SBS of BFRCs. Moreover, clinically, light exposure might be jeopardized by the hard access of the LCU in terms of the position of the teeth in the mouth (distance to target) and damaged or debris-contaminated light-curing tips, among others, which can also affect the amount of light delivered to the restorations.[1,18] In addition, it was observed that LCUs in dental offices are mostly poorly maintained and can deliver inadequate light output.[1,18] This is a limitation of the present study, as light could always be delivered from a favorable position, and maintenance of the LCU was performed accordingly. Future studies should focus on evaluating the use of experimental materials with increased amounts of photoinitiator and comparing shortened light-curing times for a greater diversity of composites.

CONCLUSIONS

Based on the limitations of the present study, the following conclusions can be made:

1. VPS is more greatly affected by the material tested than the light-curing mode. TEF showed higher VPS than the high-viscosity materials, TEC and TEE, in high-curing mode. Top shrinkage was more frequently observed than bottom/sides shrinkage.
2. SBS is affected by the material used, TC, and curing modes. Turbo mode showed lower SBS values than high mode, except for TEF and TEE with TC.
3. The CTS of the BFRCs studied was not affected by curing mode. However, TC reduced this property for all groups, except for TEE in high mode.
4. TEE generally showed similar or improved values for the tested properties in a shortened curing time compared with the other BFRCs, except for CTS without TC.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of New York University Committee on Activities Involving Human Subjects.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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