Light and viscosity effects on the curing potential of bulk-fill composites placed in deep cavities

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Light and viscosity effects on the curing potential of bulk-fill composites placed in deep cavities.

Short title: Curing potential of bulk-fill composites

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Abstract

Objectives: To determine the influence of light curing units (LCUs) and material viscosity on the degree of conversion (DC) of bulk-fill (BF) resin-based composites (RBCs) placed in deep cavity preparations.

Materials and methods: Four LCUs were tested: Valo Cordless, Bluephase-G2, Poly Wireless and Radii-cal. Light irradiance was determined at 0 mm and 6 mm distance to the reading sensor. The following RBCs were considered: Filtek BF, Filtek BF Flow, Opus BF, Opus BF Flow, Tetric N-Ceram BF and Surefil SDR Flow. Sirius-Z was used with the incremental technique. DC (n=3) was evaluated by spectroscopy both at top and bottom regions of deep preparations with 6 mm depth. The data were submitted to ANOVA and Tukey's test (α= 0.05). Pearson's correlation (95%) was used to verify the relation between the LCUs and the curing potential of RBCs.

Results: The DC at 6 mm depth was reduced when Opus BF, Opus BF Flow and Tetric N-Ceram BF were activated with Radii-cal. There was a positive correlation between the LCU irradiance and the bottom/top conversion ratios. The materials' viscosities did not affect the curing potential.

Conclusions: Bulk-fill composites did not present higher curing potential than the conventional composite used with the incremental technique; the most important aspect of the LCU was the irradiance ratio; and the materials' viscosity did not affect the curing potential as a function of depth. Radii-cal negatively impacted the degree of conversion at 6mm depth for most bulkfill resin composites.

Clinical relevance: Depending on the brand, bulk-fill composites may present reduced curing potential due to the light source when placed in deep cavities. Dentists should avoid LCU with acrylic tips to photoactivate bulkfill resins composites.

Keywords: bulk-fill; composite; depth of cure; light curing units; polymerization; viscosity

Introduction:

The bulk-fill resin-based composites (RBCs) were developed to optimize clinical time and minimizing adversities from the incremental technique [1]. Available in regular and flowable viscosities they are not necessarily a great technological leap [2], but the result of a series of facts that ended up converging on the possibility of using this class of materials in clinical situations [3-6].

Due to the placement of thicker increments, the need for increased curing light transmittance becomes crucial for optimal polymerization and ultimately the clinical success of bulk-fill RBCs. It is known that the use of light curing units (LCUs) that have high radiant exitance and that emit a wavelength within the absorption spectrum of the photoinitiators are fundamental to initiate, and provide sufficient polymerization [7-10]. Many LCUs are available in the dental market, varying in terms of the power supply (mains electric, or battery operated), active area of light curing tip, their ergonomic and optical design, i.e. light transmitted through fiber optic bundles ("pistol") compared with the LED diode(s) positioned within the head of the light curing tip ("stick"), activation mode, and spectral irradiance (diode type(s), wavelength(s) and power), and, obviously, the cost.

Previous studies have supported manufacturers' assertions that bulk-fill RBCs can achieve adequate depth of cure if an adequate LCU radiant emittance is used [7, 11]. On the other hand, some investigations have reported decreased degree of conversion (DC) towards the lower surfaces of bulk-fill RBCs using manufacturers' recommended curing exposure times [12, 13]. In addition to these contradictions, it is essential to consider the fact that in vitro studies carried out with bulk-fill RBCs commonly employ ideal laboratory conditions with 4 mm depth moulds [3, 7, 14, 15]. This is not according to many clinical situations in which the curing tip to material surface is usually greater than 0 mm distance and certainly more than 4 mm from the bottom of the cavity preparation, e.g. the gingival margin of a class II cavity, which is the point of failure of many posterior RBC-tooth restorations. Since manufacturers offer bulk-fill materials in a variety of compositions, a further clinical question remains the effect of material viscosity on polymerization at increased depths [7].

In view of the existing doubts so far, the main objective of this study was to determine the polymerization characteristics of bulk-fill RBCs in deep material layers. Specifically, the current aims were to (a) characterize the polymerization ability of bulk-fill RBCs when used in deep preparations, (b) determine the effect of the LCU parameters' of irradiance on the polymerization ability of bulk-fill RBCs; and (c) analyze whether the viscosity of the bulk-fill RBC influences the polymerization ability.

The hypotheses of the current study were, that:

I. bulk-fill composites would present higher curing potential than a conventional composite used with the incremental technique regardless of the LCU used;

II. the influence of the LCU on the polymerization capacity at great depths would be dependent on the tip irradiance;

III. the low-viscosity bulk-fill RBC would have greater polymerization ability in deep preparations when compared with the higher viscosity materials.

Materials and methods:

Materials:

Four light emitting diodes (LED) LCUs were investigated: two single diode (so-called, "monowave") LCU types; Poly Wireless (Kavo Kerr, Joinville, SC, Brazil) and Radii-cal (SDI, Victoria, Australia), and two multiple diode (so-called, "polywave") LCU types; Bluephase G2 ('high power' mode; Ivoclar Vivadent, Schaan, Liechtenstein), and Valo Cordless ('standard mode'; Ultradent, South Jordan, UT, USA) (Table 1).

Seven commercially available RBCs were tested: a conventional, non-bulk-fill material (control; tested by the incremental insertion technique – Siriuz-Z (DFL, RJ, Brazil); three bulk-fill RBCs of paste-like viscosity - Filtek Bulk Fill (3M ESPE, St Paul, MN, USA), Opus Bulk-fill APS (FGM, Joinville, SC, Brazil) and Tetric N-Ceram Bulk Fill (Ivoclar Vivadent), and three bulk-fill RBCs with lower viscosity - Filtek Bulk Fill Flow (3M ESPE), Opus Bulk-fill Flow APS (FGM), SureFil SDR Flow (Dentsply, Milford, DE, USA). Table 2 shows the RBCs specifications, according to manufacturer's information.

Methods:

Light irradiance (mW/cm^2) analysis:

The internal diameter of each LCU tip was measured with a digital caliper (Mitutoyo, Japan) to calculate the effective tip area of each LCU. The power (mW) of all LCUs was measured using a power meter (Ophir 10A-V2-SH, Ophir Optronics, Har-Hotzvim, Jerusalem, Israel) connected to a NOVA microprocessor (Ophir Optronics) (Figure 1). With these data it was possible to determine the irradiance for each LCU. For each LCU, irradiance readings were performed with the light tip juxtaposed to the power meter (0 mm) and also 6 mm from the sensor surface. The ratio between 6 to 0 mm depths was calculated to estimate light collimation and was named as "light irradiance ratio".

All procedures of power measurement were also performed trough a standardized area, to simulate the conditions used in the Fourier-transformed infrared (FTIR) spectroscopy measurements, by using a black tape with a 5 mm diameter hole.

Degree of conversion:

The DC was determined by FTIR (n=5), using a spectrometer equipped with an attenuated total reflectance (ATR) diamond device (Brüker Optics, Ettlingen, Germany). To evaluate the DC close to the LCU tip, a black-color plastic mold with 5 mm in diameter and 0.1 mm in thickness was used. The mold was positioned directly onto the diamond ATR crystal, followed by the insertion of the RBC in a single increment. A transparent polyester strip was then positioned on the RBC increment and the excess was removed by hand pressing a glass slide over this set. The DC at the top area was also used as way to estimate the highest DC for the LCUs and materials tested without the influence of material thickness.

To evaluate the DC at 6 mm depth, a black-color plastic mold, 5 mm diameter, 6 mm thickness, demarcated at 2, 4 and 6 mm, was used to guide the insertion of the increments. The matrix was positioned directly on the diamond ATR crystal followed by insertion of the increments according to the commonly used techniques:

a) Incremental (control): Sirius-Z RBC was used in 3 increments of 2 mm thickness, always followed by the photoactivation.

b) Bulk-fill RBCs of low-viscosity associated with conventional RBC as a cover: the low-viscosity bulk-fill RBC was used up to the 4 mm mark, when the photoactivation process was carried out. Over this material, one more increment (2 mm in thickness) was inserted with conventional RBC. To reduce variability, the same RBC employed in the incremental technique was used (Sirius-Z).

c) Bulk-fill RBCs of regular-viscosity: the regular-viscosity bulk-fill RBC of was used up to the mark of 4 mm, when the photoactivation process was carried out. Over this increment, one additional increment with 2 mm thickness was inserted with the same material and photoactivated. The photoactivation protocols followed the respective manufacturers' recommendation.

One split-rubber-based matrix used to surround the plastic matrix and avoid light exposure on the side areas as well as reflection from the metallic parts from the ART accessory, which might otherwise overestimate DC. The FTIR spectra were collected from the uncured composite and also immediately after photoactivation of each increment. Spectra were obtained with 32 scans and 4 cm resolution $^{-1}$ of the uncured and cured RBCs. The interval between 1,800 and 1,600 cm^{-1} was considered for the observation of the signals in 1,608 and 1,638 cm^{-1}, corresponding to the aromatic phenyl groups of bisphenol A and aliphatic functional groups of the methacrylate molecules. The DC was calculated using the ratio between the signal height at 1,638 cm^{-1} and at 1,608 cm^{-1} of the cured and uncured RBCs according to the equation:

$$\%\text{DC} = 1 - \frac{1{,}638\ cm^{-1}/1{,}608\ cm^{-1}\ \text{cured}}{1{,}638\ cm^{-1}/1{,}608\ cm^{-1}\ \text{uncured}}\ x\ 100$$

Statistical analysis:

To verify the influence of the LCUs on the DC in the top and bottom regions, multiple 2-way ANOVA followed by the Tukey's test (α= 0.05) were applied. Independent analyzes were performed for each material.

Pearson's correlation (95%) was used to verify the possibility of a relation between the LCUs irradiance conditions and the polymerization properties of RBCs. The following relations were tested for each resin composite and also with the aggregated values (average DC from all materials tested): direct irradiance *versus* DC at the top; direct irradiance *versus* DC at the bottom; 6mm irradiance *versus* DC at the top; 6 mm irradiance *versus* DC at the bottom; irradiance ratio *versus* DC ration.

In order to determine the influence of the viscosity of RBCs on DC in the top and bottom regions, the values obtained with LCU (Valo Cordless) were considered and a 3-way ANOVA was conducted and followed by Tukey's test (α= 0.05).

Results

The characterization of the LCUs is detailed in Table 1. Radii-cal showed the most significant decrease in irradiance at 6 mm depth compared to the top, maintaining only 43% of the original energy delivered. For the other LCUs, this ratio was 61%, 71% and 75% for Poly Wireless, Valo Cordless and Bluephase G2 respectively. When the light area was standardized, only Radii-Cal readings taken at 6 mm depth were lower than those at 0 mm distance. Considering the 2-way ANOVA, the factor LCU affected the DC, with the exception of the RBCs, Filtek BF Flow and Surefil SDR Flow.

Figure 2 shows both the DC mean values obtained 0.1 mm from the top surface and also the cumulative values (after 2 exposures for the bulk-fill materials and 3 for the conventional one) observed on the 6 mm depth. Table 3 shows the isolated and grouped main values of DC at 0.1 and 6 mm regions and the ratio based on the different RBCs and LCUs tested. In general, it was verified that, the LCU exerted low influence on the DC at 0.1 mm depth. When considering the 6 mm depth, Radii-cal promoted lower values than the other LCUs when Opus BF, Opus BF Flow and Tetric N-Ceram BF were analyzed. By gathering 0.1 and 6 mm depth values, Radii-cal showed statistically lower DC mean values for almost all the tested RBCs, with the exception of Filtek BF Flow and Surefil SDR Flow. Regarding the influence of the region (0.1 and 6 mm depth), only Surefil SDR Flow did not show statistical difference among the LCUs. For the other bulk-fill RBCs, the 6 mm depth region always showed lower mean values than at 0.1 mm. Conversely, Sirius-Z, applied with the incremental technique showed an inverse result, being the DC at 6 mm depth higher that at 0.1 mm. When gathered, Sirius-Z and Surefil SDR Flow approached 100% top-bottom ratio.

Table 4 shows the correlation coefficients for the comparisons between irradiance conditions and curing properties. The analyses were performed both separately for each material and also with the materials' aggregated values. It is possible to verify that the correlation between the irradiance ratio - the irradiance value obtained with the 6 mm spacer divided by the irradiance value obtained from the directly measurements on the power meter sensor - and the degree of conversion ratio (DC at the bottom region/ DC at the top region) presented the highest correlation.

The effect of material's brand, viscosity and depth on the DC values can be seen in Table 5. It is possible to observe that all the three factors significantly affected the DC, without interactions among them. With regard materials' brand, Opus BF produced higher DC values and bottom/top ratios than Filtek BF.

The more-viscous materials produced higher DC than the flowable ones but the bottom/top ratios were similar. The DC obtained at the bottom region was statistically lower than those found in the top region, regardless of materials' brands and viscosities.

Discussion

Most previous studies that analyze the curing potential of bulk-fill RBCs tend to determine the depth of cure using 4 mm thick increments [3, 7, 14, 15]. However, in clinical situations the photoactivation process of bulk-fill RBCs could represent a challenge when deeper cavities are considered, as the light has to be transmitted over thicker increments compared with that of more traditional techniques. Therefore, the current study simulated preparations with 6 mm depth that were filled with commercially available bulk-fill RBCs light cured by four LCUs and tested them in different situations. As some bulk-fill composites were dependent on the LCU tested and the conventional composite - based on 2mm increment – was not, the first research hypothesis was rejected.

Although the LCUs did not affect the DC close to the surface, they did influence those readings taken at 6 mm depth for Opus BF, Opus BF Flow and Tetric BF. Opus BF Flow showed lower conversion at 6 mm depth when the single wavelength band-based LCUs were used. This finding could be associated with the fact that this RBC presents a combination of different photoinitiators. According to the manufacturer, Opus BF and Opus BF Flow have reduced amount of CQ in their formulations and the addition of an "Advanced Polymerization System (APS)" (a given name by the manufacturer, who detains the patent of this product), which interacts with the traditional system and amplifies the polymerization capacity of RBCs. However, and in contrast to the 'flowable' RBC, the depth of cure of the more viscous material was reduced only with Radii-cal and not for Poly Wireless. Therefore, the reduced DC promoted by Radii-cal is likely to be associated with a high dispersion of light than the fact that this LCU does not emit a second peak of light. This statement can be supported by the results found with Tetric N-Ceram BF that also has an alternative initiator system.

Tetric N-Ceram BF has in its composition, "Ivocerin", an alternative photoinitiator based on germanium salt derivative and sensitive to wavelengths of violet-blue light with the maximum peak of absorption around 410 nm [4]. When the Tetric N-Ceram BF was placed as a 4 mm thick increment and light-cured, the DC mean values were lower than 50% for all LCUs tested, but after the insertion of the second increment and the additional exposure to light, the DC mean values increased and the results were statistically similar for the top region - with the exception of those samples activated with Radii-cal, which produced a top-bottom ration lower than 80%. In contrast, Poly Wireless is also a single wavelength band LCU – a contradictory term for a single diode LCU - and produced satisfactory conversion on the bottom region, being not different than the multiwave LCUs Valo or Bluephase. In other words, it seems that the final conversion at the bottom region is a fact related to the ratio between the light irradiance close to the surface to that at 6 mm depth than the number of peaks emitted by LCU. Indeed, the need for alternative photoinitiators to be sensitized by the violet spectrum has been previously reported [16]. The violet spectrum is less likely to reach greater depths due to the absorption of most of the violet light in the upper layers of the RBCs [17]. Another explanation for the lack of effectiveness of violet light is due to the relation between the wavelength of light and the dimensions of the inorganic filler particles. According to the Rayleigh-scattering law, filler particles are more likely to scatter shorter wavelengths and therefore the violet spectrum suffers greater light attenuation when compared with the blue spectrum [18]. A systematic review concluded that the multiwave LCUs are useful but not essential for activation commercially available RBCs containing alternative photoinitiators [19]. Like that, the activation of the alternative photoinitiators will be dependent on the total irradiance emission and the lower irradiance loss of the LCUs.

Sirius-Z was tested as a control group as a conventional material that required an incremental placement technique in 2 mm thicknesses, and its depth of cure was not affected by the LCUs tested in the current investigation. This finding is explained by the fact that the 2 mm thick increments and light exposures were overlapped with a longer exposure time and consequent increase of the final DC. In this way, it was possible to achieve a top-bottom ratio close to 100%. The effect of such light exposure "overlapping" is also possible to see with all bulk-fill composites as there is a clear trend of DC increase at the bottom part when the second increment is placed (Figure 1).

SureFil SDR Flow was not influenced by the different LCUs tested. Considering the DC at the bottom region after the second increment, it did not present significant statistical differences in the DC mean values in relation to the top region and it showed a top-bottom ratio close to 100%. The efficiency of the polymerization at great depths of SureFil SDR Flow should be attributed to its higher translucency, which increases the transmission of light through the material [20]. In addition, the presence of a photo reactive group of urethane-based methacrylate monomer is capable of interacting with the CQ, allowing an increase in the DC. Although it exhibits 68% by weight of filler content, which could increase its viscosity and negatively influence the results of DC and polymerization depth, the low viscosity of SureFil SDR Flow is due to the presence of TEGDMA as the diluent monomer. The absence of strong intermolecular secondary interactions, such as hydrogen bonds, in addition to the low viscosity and high flexibility, give to TEGDMA high monomeric conversion values, and is a strategy to increase the DC [21].

The second objective of the study was to determine the effect of the LCU irradiance parameters on the polymerization ability of bulk-fill RBCs. The second research hypothesis, which considered that the influence of the LCUs on the polymerization capacity at increased depths would be dependent on the irradiance directly emitted by the LCU output, was rejected, both by the statistical analyzes of each material and also by the Pearson's correlation (Table 4). Indeed, the LCU's irradiance ratio presented the highest correlation with the depth of cure. As the distance affects the amount of light that arrives at the RBC, the specimens were activated at a distance of 6 mm to reproduce a clinical situation of deep preparation and the light irradiance was checked with the light-curing tip positioned close to the power meter sensor as well as at 6 mm distance [22]. In this scenario, Bluephase G2, Valo Cordless and Poly Wireless presented top-bottom ratios of 75%, 71% and 61% respectively and Radii-cal only 43%. The large reduction of irradiance of the Radii-Cal in comparison with the others LCUs is probably related to the acrylic-based lens used in its tip which interferes in the light passage - which may be related to the refractive index or degree of translucency of the material used in the tip - and consequent decrease of the irradiance.

The influence of material viscosity on DC and depth of cure was evaluated for Filtek and Opus RBCs that are commercially available in two viscosities. The DC mean values were statistically higher for the more viscous materials and the bottom-to-top ratio was similar for both, rejecting the third hypothesis. It was expected that the low-viscosity bulk-fill RBCs would have a greater capacity of polymerization in deep preparations than the regular-viscosity ones due to the greater mobility of monomers in the less viscous media and the fact that the increased amount of filler particles hinders the passage of light through the composite [23]. The current outcomes might be justified by the different photoactivation times used for Opus BF and Opus BF Flow RBCs, being 30 and 20 seconds, respectively. The low-viscosity of Filtek BF Flow can be also related to the presence of procrylat (2,2-bis[4-(3- methacryloxypropoxy)phenyl]propane), UDMA and Bis-EMA in its organic matrix. Although Bis-EMA is an analogue to Bis-GMA and has a high molecular weight, the absence of two hydroxyl groups is responsible for its lower viscosity and higher conversion [21]. The polymers formed from Bis-EMA and modified-urethane monomers with reduced viscosity tend to produce high DC values when compared to the typical Bis-GMA/TEGDMA resin matrices. However, the presence of higher molecular weight monomers such as Bis-GMA, Bis-EMA and UDMA may have hampered the mobility of reactive species at greater depths and influenced the final DC of the composite.

In addition, because of the low and inherent mechanical properties of the low-viscosity RBCs, the restorative technique requires a final 2 mm thick layer with a more resistant and viscous RBC to obtain higher resistance to wear [24]. Then, the second increment of the low-viscosity RBCs was performed with conventional RBC and may have influenced the low final DC mean values in relation to the regular-viscosity RBCs. Another explanation is the fact that the low-viscosity RBCs have a higher proportion of organic resinous material to be activated [25] than in the high-viscosity RBC and, maybe, the light exposure time would need to be prolonged.

Although the present study aimed for simulations that more closely resemble clinical conditions, it is important to note that the conversion reading was performed immediately after the photoactivation of each increment for all tested LCUs and RBCs groups. So, the DC values found can be altered based on time and late polymerization and represents a limitation. Another limitation from the current study is that the used method does provide proper information of how the light irradiance is distributed across the wavelength bands; so additional studies are necessary with the integration of wavelength spectra analyses.

Conclusions

Considering the aforementioned results and discussion, it is therefore possible to conclude that:

- regardless of the LCU used, bulk-fill composites did not present higher curing potential than the conventional composite used with the incremental technique;

- the most important parameter to predict the curing ability of bulk-fill composites in deep cavities was the irradiance ratio between 6 and 0 mm depths and not solely the tip irradiance; and

- that the material’s viscosity did not affect the curing potential, determined by the bottom to top conversion ratio.

Compliance with Ethical Standards

Rodrigo Antonio Modena declares that she has no conflict of interest. Conflict of Interest: Larissa Maria Cavalcante declares that she has no conflict of interest. Mário Alexandre Coelho Sinhoreti declares that she has no conflict of interest. William Palin declares that she has no conflict of interest. Luis Felipe Schneider declares that has received consultant honorarium from DFL Company.

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Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors

Informed consent: For this type of study, formal consent is not required.

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Captions and legends

Figure 1: Sensor "cap" was removed (A) and it was possible to observe the 20 mm diameter sensor (B). This allowed the positioning of the same molds used for the FTIR measurements (C) and also direct contact of all light tips (D).

Figure 2: DC values obtained on the subsurface (0.1 mm) and also the cumulative values observed on the 6mm depth (after 2 exposures for the bulk-fill materials and 3 for the conventional one).

Table 1. Specifications and irradiance values of light curing units.

Code	Light curing unit	Emission Spectrum (nm)	Effective tip diameter (mm)	Power (W)	Effective tip area (cm^2)	Irradiance (mW/cm^2)	Ratio (%) 6 – 0 mm	Irradiance (mW/cm^2) with standardized area	Ratio 6 – 0 mm with standardized area
VC	Valo Cordless (Standard mode)	395-480	9.60	0 mm - 753 6 mm - 537	0.72	0 mm - 1046 6 mm - 746	71	0 mm - 889 6 mm – 2158	2.42 times
BP	Bluephase G2 (High power mode)	385-515	8.40	0 mm - 810 6 mm - 610	0.55	0 mm - 1472 6 mm - 1109	75	0 mm - 973 6 mm – 2737	2.92 times
PW	Poly Wireless	420-480	7.50	0 mm - 375 6 mm - 230	0.44	0 mm - 852 6 mm - 522	61	0 mm - 750 6 mm – 1053	1.4 times
RC	Radii-Cal	440-480	6.30	0 mm - 450 6 mm - 195	0.31	0 mm - 1450 6 mm - 629	43	0 mm - 1043 6 mm - 974	0.93 times

Manufacturer (Batch): Ultradent (C53374); Ivoclar Vivadent (227801); Kavo (2013107009); SDI (52994).

Table 2. Specifications of investigated materials (manufacturer' information).

Code	Material	Manufacturer / Batch	Shade	Organic Matrix	Filler	Filler Loading (% P / % wt)	Photoinitiator	Photoactivation time	Needs coverage
SZ	Sirius-Z	DFL 16091208	A1	Bis-EMA, Bis-GMA, UDMA, TEGDMA	Aluminum Borosilicate and glass of zirconia	77-78% / 62-63%	CQ	20 s	No
FBF	Filtek Bulk Fill	3M ESPE N692414	A1	AFM, AUDMA, DDMA, UDMA	Silica/Zirconia, YbF3	76.5% / 58.4%	CQ	20 s	No
OBF	Opus Bulk Fill APS	FGM 271013	A1	Uretane-dimetacrylic monomers	Silica	79% / -	APS	30 s	No
TBF	Tetric N-Ceram Bulk Fill	Ivoclar Vivadent T40644	IVW	Bis-GMA, Bis-EMA, UDMA	Glass of Bario, oxides and pre-polymers, and YbF3	81% / 61%	CQ, IVOCERIN, TPO	10 s	No
FBFF	Filtek Bulk Fill Flow	3M ESPE N821165	A1	Bis-GMA, Bis-EMA, Procrylat resins, UDMA, TEGDMA	Silica/Zirconia, YbF3	64.5% / 42.5%	CQ	20 s	Yes
OBFF	Opus Bulk Fill Flow APS	FGM 010816	A1	Uretane-dimetacrylic monomers	Silica	68% / -	APS	20 s	Yes
SDR	SureFil SDR Flow	Dentsply 1512233	Uni	EBPADMA, modified UDMA, TEGDMA	Glass of Ba-Al-F-B-Si and glass of St-Al-F-Si	68% / 45%	CQ	20 s	Yes

AFM - addition-fragmentation monomers; APS - advanced polymerization system; AUDMA - aromatic dimethacrylate; Bis-EMA – ethoxylated bisphenol-A dimethacrylate; Bis-GMA – bisphenol-A diglycidyl ether dimethacrylate; CQ - camphorquinone; DDMA – 1, 12-dodecanediol dimethacrylate; EBPADMA - ethoxylated bisphenol-A dimethacrylate; TEGDMA – triethyleneglycol dimethacrylate; UDMA – urethane dimethacrylate; Glass of Ba-Al-F-B-Si – Barium alumino fluoroborosilicate glass; Glass of St-Al-F-Si – strontium alumino fluoroborosilicate glass; YbF3 ytterbium trifluoride.

Table 3. Influence of light curing unit on the degree conversion as a function of depth for each material tested.

RBC	LCU (DC)	Top	Bottom 6 mm	Ratio (%) top/bottom	Grouped average
OBF	Valo Cordless a	73.0 ± 2.6 A,a	68.3 ± 1.5 A,a	93.5	89.2
	Bluephase G2 a	72.8 ± 2.7 A,a	67.6 ± 2.8 A,a	92.5	
	Poly Wireless a	71.0 ± 2.1 A,a	67.6 ± 0.2 A,a	92.6	
	Radii-Cal b	68.1 ±4.7 A,a	57.1 ± 0.9 B,b	78.3	
OBFF	Valo Cordless ab	67.0 ± 2.4 A,a	63.5 ± 3.4 B,a	93.9	91.7
	Bluephase G2 a	67.5 ± 0.9 A,a	67.2 ± 2.5 A,a	99.5	
	Poly Wireless ab	67.4 ± 1.2 A,a	59.7 ± 2.4 B,a	88.4	
	Radii-Cal b	64.9 ± 0.6 A,a	57.3 ± 2.3 B,b	84.8	
FBF	Valo Cordless a	70.5 ±1.9 A,a	63.0 ±1.4 B,a	89.3	88.2
	Bluephase G2 ab	68.0 ±1.0 A,ab	61.6 ±1.3 B,a	87.2	
	Poly Wireless ab	65.9 ±2.8 A,ab	63.1 ±1.8 A,a	89.3	
	Radii-Cal b	64.6 ±0.5 A,b	61.4 ±2.9 B,a	87.1	
FBFF	Valo Cordless a	64.1 ±2.7 A,a	55.6 ±1.1 B,a	86.7	86
	Bluephase G2 a	63.2 ±2.2 A,a	57.0 ±0.9 B,a	88.9	
	Poly Wireless a	62.7 ±1.6 A,a	54.7 ±2.5 B,a	85.3	
	Radii-Cal a	61.8 ±1.4 A,a	53.4 ±1.7 B,a	83.3	
TBF	Valo Cordless a	62.6 ± 0.6 A,a	53.5 ±2.2 B,a	85.4	83.2
	Bluephase G2 a	58.3 ±1.2 A,a	54.8 ±1.5 A,a	87.5	
	Poly Wireless a	58.2 ±1.5 A,a	54.8 ±1.7 A,a	87.6	
	Radii-Cal b	58.1 ±0.5 A,a	45.3 ±2.0 B,b	72.3	
SDR	Valo Cordless a	61.3 ±2.5 A,a	60.5 ±1.3 A,a	96.8	99.3
	Bluephase G2 a	62.5 ±0.7 A,a	62.6 ±1.4 A,a	100.2	
	Poly Wireless a	61.9 ±1.8 A,a	63.2 ±1.0 A,a	101.1	
	Radii-Cal a	61.7 ±1.0 A,a	62.0 ±2.2 A,a	99.1	
SZ	Valo Cordless ab	66.3 ±0.2 A,a	66.0 ±0.6 A,a	98.7	99.9
	Bluephase G2 a	66.9 ±1.2 A,a	68.1 ±0.9 A,a	101.8	
	Poly Wireless ab	64.9 ±1.0 A,a	67.5 ±0.9 A,a	100.9	
	Radii-Cal b	64.7 ±0.7 A,a	65.8 ±1.1 A,a	98.4	

To calculate the top/bottom ratio (%), was used for each RBC the top value obtained by the best LCU. Different letters indicate statistically significant difference for each material (capital letters horizontally and small letters vertically). Significance values (p) for the two-way ANOVA comparisons for each material tested (OBF - LCU p=<0.001, region p=<0.001, LCU*region p=<0.001; OBFF - LCU p=<0.004, region p=<0.001, LCU*region p=<0.154; FBF - LCU p=<0.009, region p=<0.001, LCU*region p=<0.151; FBFF - LCU p=<0.077, region p=<0.001, LCU*region p=<0.678; TBF - LCU p=<0.001, region p=<0.001, LCU*region p=<0.001; SDR - LCU p=<0.411, region p=<0.313, LCU*region p=<0.750; SZ - LCU p=<0.039, region p=<0.004, LCU*region p=<0.127).

Table 4: Correlation coefficients for the comparisons between irradiance conditions and curing properties.

Correlation	OBF	OBFF	FBF	FBFF	TBF	SDR	SZ
Direct irradiance * DC top	0.2622	0.4663	0.2052	0.3497	0.3435	0.4489	0.2676
Direct irradiance * DC bottom	0.5431	0.3111	0.9693	0.1099	0.5047	0.0249	0.0180
6 mm irradiance * DC top	0.6087	0.3310	0.5265	0.4465	0.1305	0.5254	0.9162
6 mm irradiance * DC bottom	0.3039	0.8581	0.4503	0.8278	0.3012	0.1907	0.3942
Irradiance ratio * DC ratio	0.9130	0.9283	0.3131	0.9502	0.8863	0.1107	0.5803
	Aggregated values						
Direct irradiance * DC top	-0.2512						
Direct irradiance * DC bottom	-0.3802						
6 mm irradiance * DC top	0.5655						
6 mm irradiance * DC bottom	0.4451						
Irradiance ratio * DC ratio	0.9521						

The correlation tests were performed both separately for each material and also with the materials' aggregated values.

Table 5: Degree of conversion as a function of depth, materials' brand and viscosity.

Brand	Viscosity	TOP A	BOTTOM B	Bottom/top ratio (in %)
Opus BF	High a	73.0 ± 2.6 A,a	68.3 ±1.5 B,a	95.5
	Low b	67.1 ±2.4 A,b	63.5 ±3.4 B,b	93.9
Filtek BF	High a	70.5 ±1.9 A,a	63.5 ±1.4 B,a	89.3
	Low b	64.1 ±2.7 A,b	55.6 ±1.1 B,b	86.7

To perform the comparisons were used the DC values obtained by the LCU Valo Cordless. Different letters indicate statistically significant difference for each material (capital letters horizontally and small letters vertically). Significance values (p) for the three-way ANOVA comparisons (RBC $p \leq 0.001$; viscosity $p \leq 0.001$; region $p \leq 0.001$; RBC*viscosity $p \leq 0.421$; RBC*region $p \leq 0.328$; viscosity*region $p \leq 0.928$).

Figure 1

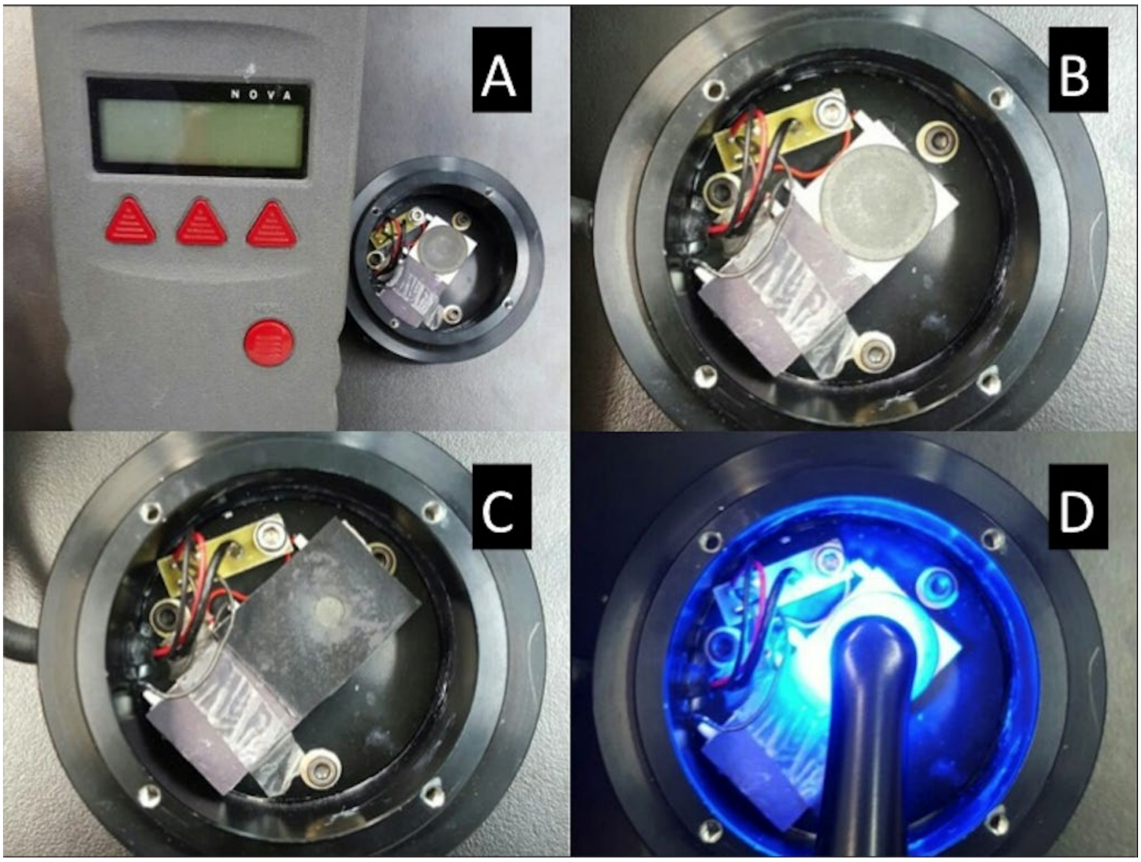
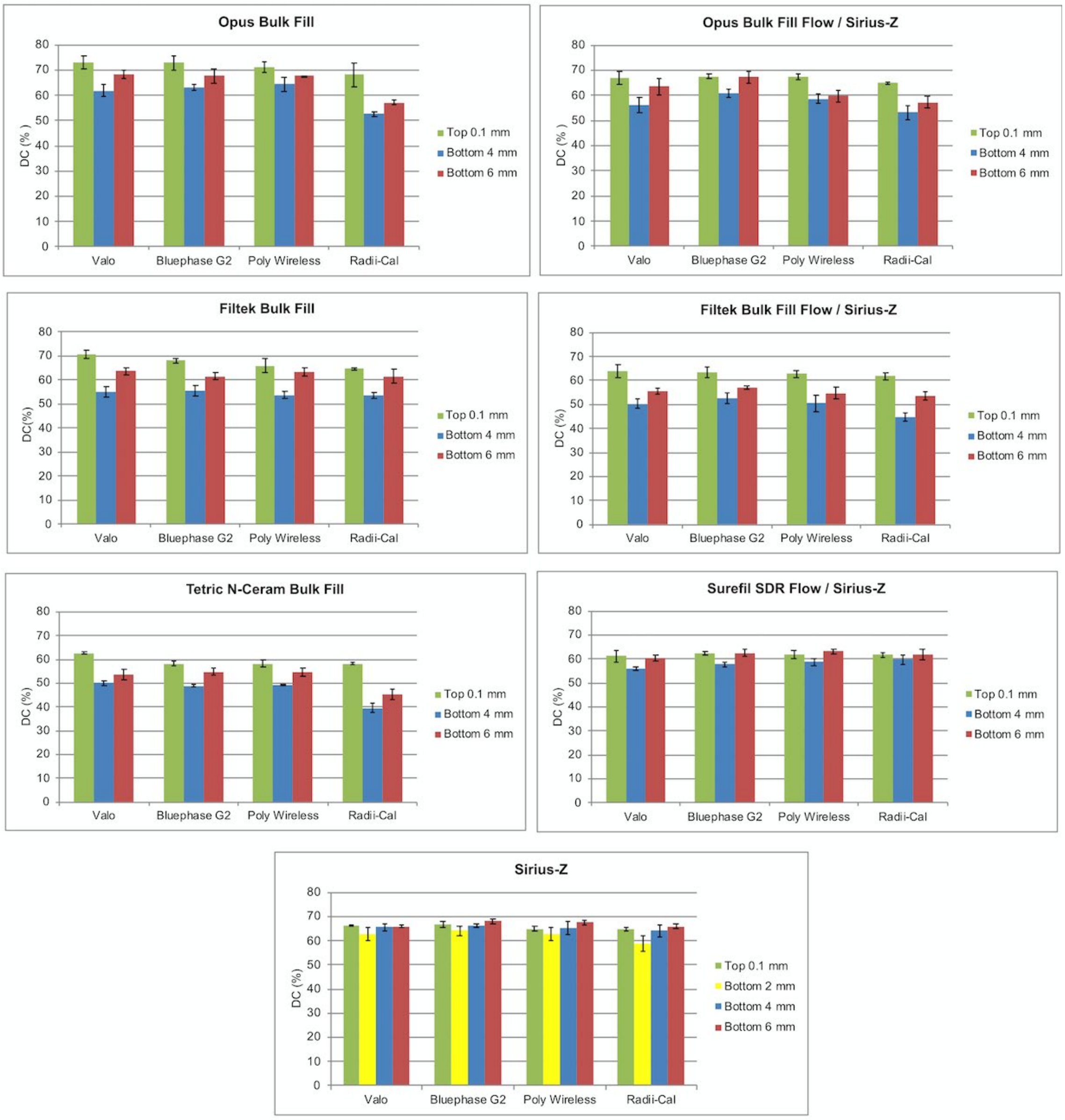


Figure 2


Opus Bulk Fill
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Opus Bulk Fill Flow / Sirius-Z
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Filtek Bulk Fill
DC(%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Filtek Bulk Fill Flow / Sirius-Z
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Tetric N-Ceram Bulk Fill
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Surefil SDR Flow / Sirius-Z
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 4 mm
Bottom 6 mm
Sirius-Z
DC (%)
0 10 20 30 40 50 60 70 80
Valo
Bluephase G2
Poly Wireless
Radii-Cal
Top 0.1 mm
Bottom 2 mm
Bottom 4 mm
Bottom 6 mm